MODERATE DEPTH LUNAR DRILL

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SUMMARY OF MODERATE DEPTH LUNAR DRILL DEVELOPMENT PROGRAM FROM ITS CONCEPTION TO JULY 1, 1972

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FINAL REPORT
LUNAR DRILL TEST SUPPORT

Contract No. NAS 8-26487

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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ABSTRACT

This document has been prepared and submitted in accordance with the requirements of Contract NAS 8-26487, Statement of Work and the Change Notice dated 4 May 1972.

The document summarizes the Moderate Depth Lunar Drill Development Program from its conception to the present time in sufficient detail to provide an information base in the event that the program is reinstated at some future time. Recommendations are presented for future concept improvements and developments.

The report includes a Documentation List reflecting all documents which relate to this program. Detail design drawings, analyses, test reports and other information, which are referenced, have been forwarded previously to the Lunar Drill Program Office, MSFC in accordance with the program requirements and are not included in this report.

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1. INTRODUCTION

Over a decade ago, landing a man on the moon and returning him to earth safely became a national goal calculated to unite and to give a new dimension to our countrys' aim for peace and for the betterment of mankind.

The achievement of this goal has been repeated a number of times to obtain first hand observations of the lunar surface in typical areas. The last planned surface survey will be made during the final Apollo Mission in December, 1972.

The surface samples and small cores obtained by the astronauts have given important clues to the geologic processes which formed the areas surveyed and perhaps to the origin of the moon, earth, and the other solar system elements. If man is to continue to attempt to answer the famous 15 questions posed at the Woodshole Massachusetts Space Science Board Conference in 1965 and to follow the recommended programs for detailed geological studies and measurements and to observe those phemomena which are time dependent, he must return to the moon for extended periods. A significant number of the major scientific questions, concerning the early history of the moon, the crustal composition, and the surface processes of the past can best be approached by taking deep samples with a coring drill. The type of drilling apparatus, the number of holes, and the drilling time probably would, in turn, require a lunar base for support.

A moderate-depth lunar drill development appeared to be a reasonable starting point for the past-Apollo-lunar exploration effort since it was consistent with most of the restraints of funding, schedule, and cargo and other capacities of the planned Lunar Module configuration. The 100-foot depth with a 95 percent core recovery goal, if achieved, would yield a considerable amount of geological information. If the technological breakthroughs for its specific mission could be achieved, the resultant designs would provide a base from which a drill with a capability of drilling to a 1,000-foot depth could be developed readily.

The initial system research and development phase for the Moderate Depth Lunar Drill development has been completed except for a test which would have shown how the engineering model system would have held up under field conditions. This test was eliminated due to a NASA internal funding situation.

The purpose of this report is to cover the Moderate Depth Lunar Drill Development from its conception to its present status in sufficient detail to provide an information base in the event that the development is continued at some future time. In addition, the recommended future developments are described.

2. PROGRAM OBJECTIVES AND ACCOMPLISHMENTS

The overall objective of the Lunar Drill Program was to develop a lunar drill capable of taking lunar surface cores to depths of at least 100 feet and to examine methods and techniques of extending this concept beyond 100 feet.

The Lunar Drill System was brought to its present stage of development over an elapsed time of 7 years. The development work was carried out under three contracts.

2.1 CONTRACT NAS 8-20547 - DEVELOPMENT OF A SUBSURFACE DRILL SYSTEM FOR POST-APOLLO MISSIONS, JULY 1965 - MARCH 1967

2.1.1 Objectives

The specific objectives of this contract were to demonstrate the feasibility of the Westinghouse concept by performing laboratory feasibility tests on specific high-priority elements during the first 120 days of the contract and to develop an engineering model which was a suitable facsimile of a lunar drill prototype capable of taking core samples in dry rock to a depth of 100 feet. The high priority elements were:

- To demonstrate the mechanical arrangement to provide coolant to the bit
- To demonstrate the manner of chip removal.
- To demonstrate the feasibility of rotary diamond drilling without using a liquid or compressed gas chip flush.

If these elements proved feasible, the drill development work was to be accomplished within the following restraints:

a. The total weight of the drill including any coolant material, but excluding the power supply, should not be greater than 200 pounds.

b. The weight of the lunar module which might be applied to the drill during lunar drilling operations was approximately 5,000 pounds mass. Because of mounting restrictions on the vehicle and the reduced lunar gravity, the practical limitation for thrust reactance was set at approximately 400 pounds.

c. The maximum power level for the drill was not to exceed 5 kW.

d. Hole cave-in was to be prevented for the first 5 feet.

e. Drill system was to be installed and operated by a space-suited astronaut.

f. The deliverable items on the contract were to be:

- An engineering model of the drill
- One unassembled engineering model
- A set of engineering, shop, and assembly drawings of the engineering model of the drill
- Monthly, quarterly, and final reports.

2.1.2 Program Accomplishments

Two engineering models were delivered. The assembled model was used to demonstrate the workability of the system for drilling in dry basalt rock and to recover cores. The other engineering model was shipped unassembled for the testing of component parts and to provide spare parts for the assembled drill model.

A complete set of drawings were delivered in the form of aperture cards.

Whereas the engineering model drill system did not achieve all of the objectives of the program, significant advances were made toward the goal of developing a reliable tool for the post-Apollo missions.

- Diamond rotary drill bit technology was advanced to the point where over 10 feet of basalt could be drilled with an internally cooled bit, and to where there was evidence that the internal coolant might not be necessary. These advances were demonstrated by one or more tests.
- A control was developed for the automatic control of the drilling factors, once the settings were made, and an alternate manual control capability was provided.

- Automatic protection circuitry was developed to shutdown the drill system where the automatic control settings were exceeded and for operator safety. Indicators were provided to indicate the shutdown cause.
- Systems to provide rapid recovery of cores and to remove drilling chips were demonstrated.
- A bit cooling system was developed, including a rotary joint which changed the bit coolant flow from a straight to a rotary path under vacuum conditions.
- A multihorsepower dc motor, which would operate under high vacuum conditions.
- A solid lubricated gearbox, which gave promise of operation in a high-vacuum environment as the result of tests on solid lubricated gears and bearings.
- A method of casing the hole for the first 5 feet to prevent cave-in was developed.
- A drill system was provided which could be assembled and operated by an astronaut under lunar conditions.

The weight objective was not achieved. The use of new engineering materials and the potential elimination of the bit cooling system gave promise of meeting the weight restraint.

The limited laboratory system testing indicated that further development would be required in the following areas:

a. Diamond Bit Design - To increase the bit life to at least 100 feet of basalt drilling.

b. Chip Removal - to test this system under operating conditions and to optimize the component operation.

c. Gearbox - to life test in a high vacuum and to improve components to assure that it would operate reliably in a lunar environment.

d. Drill String Coupling - to improve method of assembly so that the task could be performed easily easily by a space-suited astronaut.

e. Drill Motor - to improve the cooling design so that the motor would operate reliably in a lunar environment for its expected life.

f. Automation Techniques - to reduce the astronaut's activities and time spent in drilling a 100-foot deep hole in the lunar surface.

2.2 CONTRACT NAS 8-20845 - INVESTIGATION AND IMPROVEMENT IN THE MODERATE DEPTH LUNAR DRILL, JULY 1968 - JUNE 1970

2.2.1 Objectives

The research and development work performed under this contract was to cover the following bit and chip removal study programs:

a. Diamond Bit Research Study: Objective - Developing a bit or bits capable of drilling through at least 100 feet of basalt without the use of chip flushing agents.

b. Bit Manufacturing Program: Objective - Developing a bit supplier to the point where he is capable of delivering high quality diamond bits to a rigid specification.

c. Chip Removal Study: Objective - Devising a system which is capable of removing chips expeditiously from the bit-rock interface, transporting the chips up the barrel, and depositing them in the internal chip basket.

d. Chip Removal Study Empirical Program: Objective - Developing experimental techniques to lift the chips 15 feet and to deposit them in an internal chip basket, monitoring the movement of the chips by visual or other means, evaluating the efficiency of the system to deposit the chips in the chip basket, verifying the results with regard to variations in the drill system parameters, and providing the means of visually monitoring and recording the performance of the Chip Removal System.

The Program Plan philosophy was based upon the following opinions which were developed during the previous contract (NAS 8-20547):

- That destructive diamond temperatures are not developed during progressive dry drilling basalt, and that this type of experienced damage results from continuing efforts to drill after a failure of the chip removal mechanism.

- That a frequent cause of chip removal failure is the adverse combination of high thermal expansion of the bits and core barrels, and the small dimensional clearances between the drilled hole and the chip removal auger flights.
- That a bit design based upon scientifically derived data and precision manufacturing will drill a hole in basalt and will approach the hole depth/bit objective.

2.2.2 Program Accomplishments

The bit life in Dresser basalt was increased to 25 feet. The Diamond Bit Research Study indicated the following:

a. Diamond Orientation and Protrusion - A 7-1/2 degree rake appeared to contribute heavily to bit life and to obtaining the diamond protrusion which is necessary to produce the most efficient flow of chips across the bit face.

b. Diamond Pattern - A diamond pattern of 81 load bearing diamonds set in 31 line circles appeared to yield the least chatter and best chip flow. The diamonds were set in a snow plow configuration in each of the six bit segments.

c. Crown Design - A 0.235-inch radius crown, containing six face chip release areas cut at a 15-degree backward rake and which fed in pairs into three auger flights, appeared to yield the best results. Diamonds set in the OD periphery help to channel the chips into the auger. The ID had six chip release areas which fed into the six chip release areas in the face. The overall design appeared to provide adequate chip flow up the highest achieved penetration rate of 4.2 inches per minute in Dresser basalt.

d. Matrix Composition - Type 4 metal powder a proprietary composition of the bit supplier, Hoffman Diamond Products, Inc., met every requirement for abrasion resistance, bonding to the blank, and for holding the diamonds in position.

e. Thrust - It was determined that 7 to 12 pounds/load bearing diamond yielded the best bit life of a 25-foot hole depth in basalt at 700 rpm. Some evidence was obtained which indicated that an optimum combination of thrust and rpm, which would give a higher penetration/revolution, might permit the goal of 100-foot bit life to be reached.

f. RPM - The effect of rpm on bit life was not established, but indications are that a lower rpm may be beneficial.

g. Water and Air Flushing - A comparison was made between drilling dry and flushing with water or air to determine the effect of a more complete removal of the chips on bit life. The water flushing increased bit life over dry drilling by a factor of 3.67 times. However, the additional life might be attributed to either more efficient chip removal, or to the lubricating or cooling effect of the water. An air chip removal test which would eliminate the latter two variables was not successful due to a chatter problem.

h. Torque - The torque at 700 rpm and 400 pounds thrust, with the bit cutting approximately 2 inches per minute, was 7 to 9 foot-pounds regardless of hole depth. The power required to turn the bit was 700 to 900 watts, or 1.07 to 1.20 horsepower. Torque sensor difficulties prevented further study.

i. Penetration Rate - The study showed that the bit life is influenced by penetration rate rather than thrust. The most successful tests were run at constant penetration rates within the test equipment limitations.

j. Drilling Temperatures - The tests showed that the drill bit did not require internal cooling. The rock temperatures near the cutting bit had temperature rises of 39°F using a sharp bit, and 198°F with a dull bit. At the bit-rock interface, the temperature of 210°F was recorded for a sharp drill bit, but was estimated to be higher due to the thermocouple size - temperature gradient relationship. Chip temperatures, measured at the top of the hole, showed a maximum temperature rise of 370°F. Core temperature measurements showed the highest temperature rise to be 80°F. Instrumented diamonds in the bit face did not have sufficient protrusion to cut rock. However, the maximum recorded temperature, presumed to be those of the chips in the rock-bit interface, was 658°F while drilling at a very low and inefficient penetration rate.

k. Rock Variations - Rock variations had an indeterminate deleterious effect on bit life and made interpretations of bit design changes difficult.

l. Bit Manufacturing Program - Improvements and innovations were made in the manufacturing methods normally employed in the manufacture of geological bits. These covered the selection of diamonds, the development of a three piece mold, the precision machining of the pips, the procurement of a suitable matrix, the development of a crown to Invar blank bond, and auger machining methods. Methods of quality control and inspection were developed. Except for a few stones/crown which were affected by the manufacturing process variables, the diamonds averaged within ±0.005 inch of the nominal on protrusion and as much as ±5 degrees on rake angle setting. The TIR measured on the bit matrix and with the bit on the test machine did not exceed 0.006 inch.

m. Theoretical Chip Removal Study - A mathematical model of basalt chip flow up an auger, and 10-, 15-, and 25-degree, auger flight designs were developed to carry chips away faster than the bit could generate them. A study showed that the most efficient chip sweep angle for the chip release areas was a 15 degree backward rake. A mathematical model of chip flow and an optimized design was made for turning the chips inwardly to a chip basket. Nonrotating interior deflecting vanes were designed to prevent chip entry port clogging.

n. Experimental Chip Removal - An experimental test setup was made using a 15-foot basalt column containing three holes, each larger than the augers and varying from each other. The tests showed that the auger and chip basket entry designs were more than adequate for any bit penetration rate attainable under existing conditions.

2.3 CONTRACT NAS 8-20845 MODIFICATION 4

2.3.1 Objectives

The objective of the Moderate Depth Lunar Drill Development Program, Modification 4 was to design and test 28 bits aimed toward a bit design which would have a life of 100 feet in basalt. Among the design and operating parameters to be studied were:

a. Determination of an optimal penetration per revolution.

b. Chip removal efficiency of the optimized design compared to an air-flush chip removal bit test.

c. Adjustment of the number of diamonds in order to be compatible with the optimized thrust and the optimal penetration per revolution.

d. Bit contours to promote chip flow across the face, to obtain better stability in the hole, and to reduce diamond breakage.

e. Sweep devices and sweepers to be added to the bit face and auger entries to move the chips positively.

f. Larger chip release areas for better chip movement.

g. Optimization of diamond patterns.

h. Rake angles of diamonds

i. The utilization of used diamonds to keep program costs down.

2.3.2 Program Accomplishment

In the work performed under Contract Modification 4, further development of the bit design and operation resulted in a greatly improved bit life. The program goal of 100-foot bit life was achieved on three bits in this phase of the program. Several other bits achieved a 50- to 95-foot drill life.

Due to the number of bits utilized to study the parameters of interest, no comparative chip removal tests were made against air chip removal techniques.

The studies covered the following variables:

a. Type of Diamond - Brown Premiers proved to be the equal of the high-grade South African Bortz which had been used in the previous Bit Research Study. The Brown Premier was substituted in the latter part of the Modification 5 effort because the others became scarce. The used stones from earlier bits were utilized as kicker stones. No conclusions were reached on their utility as face stones.

b. Diamond Protrusion - The minimal diamond protrusion appears to be 0.015 inch in a new bit.

c. Diamond Orientation - The nominal rake angle was optimized at 4.5 degrees.

d. Diamond Pattern - The OD reaming stones were set in rows which had a backward rake with respect to the direction of rotation to aid in clearing chips into the augers. The ID reaming stones were set in rows at a rake angle which push the chips down to the face-chip release areas. The face pattern proven best was 66 load-bearing diamonds arranged on 35 line circles with a spacing of 0.010 inch between line circles. The stones were arranged in rows forming outward spirals with the intention of helping to sweep the chips outwardly across the face.

e. Auger Design - The 15-degree auger helix worked well with a 0.050-inch depth and a 0.030-inch wall clearance. The three auger flights configuration appeared to be most efficient.

f. Bit Set Size - The set size, selected to be compatible with all elements of the core barrel, auger, and other design considerations, was 1.955-inches OD by 1.375-inches ID with a ±0.005-inch tolerance.

g. Thrust - Thrusts up to 2,000 pounds were used to maintain optimal penetration per revolution. The highest value was applied as the bit became dull.

h. RPM - The rpm was set at 375 to provide the best balance between long life and bit temperature.

i. Penetration Rate - The best compromise feed appeared to be 0.006 inch. This feed was set to obtain the best balance between diamond wear and diamond fracture.

j. Drilling Performance In Various Rock - The bits were optimized to drill Dresser basalt. The operating and design parameters for basalt were not optimum for granite, marble, or limestone. The granite caused fast bit wearout, but the chips augered well. Marble drilled easily but showed some tendency to auger with difficulty. Limestone drilled easily until the augers and bit face clogged up.

k. Torque - The maximal torque, recorded under an excessive 0.010 inch/revolution penetration rate, was 30 foot-pounds which at 375 rpm is 2.14 horsepower. The average torque required was substantially below this figure.

l. Bit and Chip Temperatures - There was good correlation between bit condition and bit temperature. When the bit temperature reached 500°F, the remaining bit life was found to be very limited. Chip temperatures were dependent upon auger barrel temperatures and were therefore usually lower than bit face temperature.

m. Diamond Wear - The average protrusion of the diamonds in new bits was 0.015 inch. It was found that an average measured loss of 0.006 inch in protrusion coincided with the end of useful bit life.

n. Rock Scratch Tests - A parameter was defined which established a ratio of drag to thrust.

2.4 CONTRACT NAS 8-20845 MODIFICATION 5

2.4.1 Objectives

The objectives of Modification 5 were to provide or study the following:

a. Deliver four bits of the design optimized in Modification 4.

b. Design and fabricate a 15-foot core barrel assembly.

c. Develop a design for drill rods.

d. Design and fabricate modification parts for one drive mechanism.

e. Study a collapsible bit design.

2.4.2 Program Accomplishments

a. Four bits of the optimized design were manufactured to the dimensions which were commensurate with the core barrel design. The bits were broken-in at the bit subcontractor's plant (Hoffman Diamond Products, Inc., Punxsutawney, Pa.). Due to the abnormally high bit temperatures occurring during the break-in procedure, the bits were badly damaged. No reason could be given for this phenomenon. The causative factors could have been harder and higher compressive strength rock, poor heat conduction due to new shank dimensions, or poor chip removal.

b. Core Barrel and Inner Barrel Design - A 15-foot core barrel system was designed, manufactured, and delivered. The operation of the inner core barrel was based upon its being stationary with respect to the outer core barrel. The core lifter design to accomplish this action had some potential problems which could only be determined empirically during a laboratory system test.

c. Drill Rod Design - A design was made to connect to the chuck and to the core barrel assembly.

d. Gearbox - Modification parts were made to reduce the output rational speed to 504 rpm. Further changes were recommended to reduce its speed to 375 rpm to be commensurate with the change in rpm requirements found necessary late in this contract.

e. Retractible Bit Concept - A concept was developed which appeared to be practical.

2.5 CONTRACT NAS 8-20845 MODIFICATION 9 TEST BITS

2.5.1 Objective

Four bits of the optimized design were to be tested in a manner designed to pinpoint the causative factors of the burn-in failure of the four deliverable bits, supplied under Modification 4.

2.5.2 Program Accomplishments

It was concluded that the major cause of the higher temperature of the bit failures in the previous contract modification was due to the abnormal rock physical parameters and microstructure. All tests were made in Dresser basalt whose physical parameters were well above normal. Lower temperatures and longer life could be expected with Dresser basalt of normal parameters. The bits were delivered, in a usable condition after the tests.

2.6 CONTRACT NAS 8-26487 LUNAR DRILL TEST SUPPORT, DECEMBER 1970 - JUNE 1972

2.6.1 Objective

MSFC was to be supported in its efforts to get the Lunar Drill Model ready for the field test and to support MSFC during the field tests. The field tests were to be made in the Kilbourne Crater area of New Mexico next to holes drilled using conventional drilling techniques.

Specifically, the effort was to cover:

a. Participation in preparations for field testing, including the laboratory tests to be performed at MSFC. These laboratory tests were to be conducted to determine if the lunar drill could hold up under the field testing conditions. In addition, the tests were to be selected, the test procedures prepared, and assistance was to be given during the laboratory tests.

b. Assist in the evaluation of the laboratory and field test results including the evaluation of the used drill bits.

c. Recommend an overshot device.

d. Investigate problem areas that might develop during the field test preparation of the drill system and the actual field testing and provide recommended solutions including designs in sufficient detail to permit fabrication of improved components in any competent machine shop.

2.6.2 Program Accomplishments

The following studies were conducted and support was provided during the preparations for field testing:

a. New feed motor study

b. Feed control malfunction

c. Laboratory test instrumentation plan

d. Laboratory test plans and approach

e. Drill string disassembly tool design

f. Casing bit study

g. Inner barrel study

h. Shaft whirl study

i. Core tensile determination

j. Bit break-in test support

k. Overshot design recommendation

l. Rock stabilization study

m. Test and bit evaluation

n. Core lifter study

o. Laboratory test support

The results of the laboratory testing indicated that the Lunar Drill System was ready for field testing. However, a part of task b and all of task d of paragraph 2.6.1 was not completed due to a statement of work change resulting from MSFC's lacking sufficient funds to support their personnel during the field tests. The C/N indicated that due to the unavailability of TDY funds. MSFC would not be able to extend the subject contract beyond the expiration date of 8 June 1972, for the purpose of accomplishing the field testing portion of the drill project.

It was requested, therefore, that the final report which documents the drill program from conception to the present time, be prepared in sufficient detail to provide an information base in the event the program should be reinstated in the future. The final report should include a documentation list reflecting all documents that have been generated which relates to this program. One reproducible copy of the final report would be required.

This C/N effort is embodied in this report.

3. CONCEPT AND PHILOSOPHY

3.1 CONCEPT

The Westinghouse lunar drill concept is based upon the design of an operational drill system, the E. J. Longyear Wireline Drill, which has been in widespread use for approximately 25 years.

The wireline drill system, like conventional rotary drills, consists of a drill-rig, a prime mover, drill rods, a core barrel, and a bit (figure 3-1). The unique element, which sets the wireline drill system apart from other drilling systems and techniques, is the method of core recovery. As the core is cut, it is collected in a retractable core barrel which can be lifted to the surface without withdrawing and dismantling the drill string. After a length of core is withdrawn from the retractible core barrel, the core barrel can be lowered into place inside the drill rod and drilling can be continued.

The system was adapted in the initial design to operate in the lunar environment by providing a sealed dc motor for vacuum operation, and solid metallic base lubricants for bearing and gears. However, the plans, to perform drilling tests in the laboratory at MSFC and, later on, in volcanic formations, indicated that the drill life should be greater than the operating life goal of 160 hours. For these tests, the drive motor was replaced by a motor designed to operate in earth environments, and the solid lubrication was replaced with a conventional lubrication system.

The lunar drill concept variations from the wireline approach appeared to be:

a. Had to be much lighter than any wireline drill system for the size core to be retrieved. A typical earth coring drill, excluding downhole hardware, weighs in the order of 2,500 - 3,600 lb. The double tube swivel

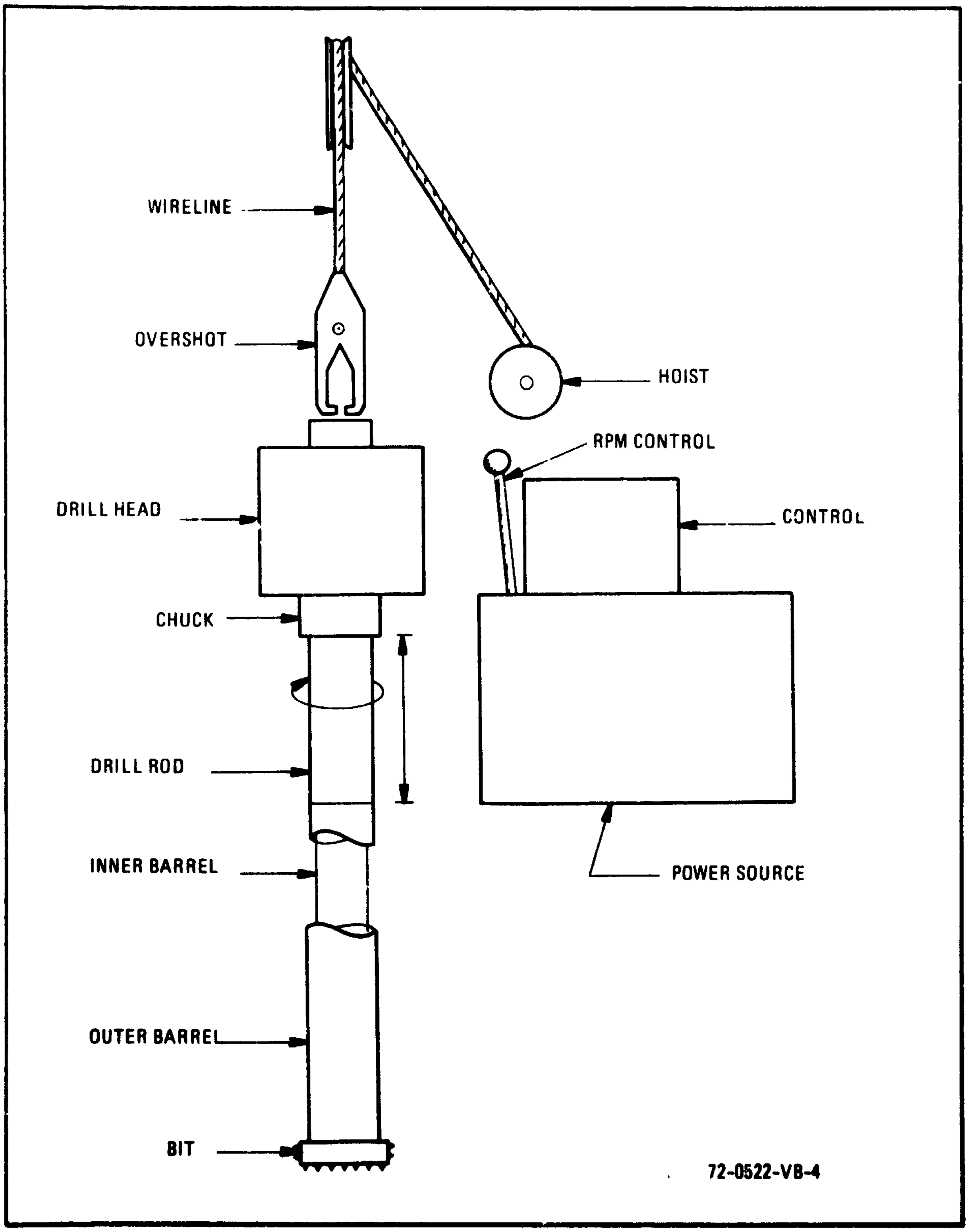

Figure 3-1. Wireline Drill Rig Components

type core barrel assembly typically weighs 46 lb for a 10-foot section, and the drill rods weigh in the order of 38 lb/10 foot length. A 15-foot core barrel assembly would then weight approximately 70 lb and the remaining 85-feet of drill pipe would weigh approximately 323 lb. Therefore, the downhole hardware alone could be approximately twice that of the overall lunar drill weight objective. Obviously, the weight could be reduced drastically since the lunar drill life objective of 160 hours operation was far less than the earth coring drill, whose rugged construction yielded a life of several years. The downhole hardware could be lightened similarly since it would be used for only one or two holes.

b. Had to operate under the lunar environment of low gravity, high vacuum, and temperature extremes. The low lunar gravity has a beneficial effect during the Lunar Drill erection since the drill, excluding the downhole hardware, appears to the astronauts to weigh less than 30 earth pounds. The lower gravity also increases the augering efficiency.

The lunar vacuum environment forbids the use of liquids for chip flushing or for lubrication of the moving parts. There is a concern that the high vacuum could inhibit the chip augering since there could be chip-to-chip, chip-to-hole-wall, or chip-to-auger cold welding.

The lunar thermal ambients require an elaborate thermal control system for the drive motor. It would be necessary to compensate for the wide temperature variations which could occur during the drilling mission and which would affect the bearing, gear, and other important clearances.

c. Had to utilize far less power. The lunar module had a power budget which would permit a maximum of 5 kW for powering the lunar drill. Later, this maximum was revised downward to 4 kW. Geological coring drills employ from 10 to 20 kW for the similar drilling applications.

d. Had to be operated by a space suited astronaut; therefore, would require less physical dexterity and physical capability.

The low order of manual dexterity and physical restraints of the spacesuit and the multitudinous other activities which must be scheduled prevents the astronaut from operating the drill on a continuous basis. Therefore, the drill must have a control which would automatically control the drill according to the factors set by the astronaut, react to out of limit conditions, and indicate the causative factor. With this control, the astronaut's activities would be limited to drill erection and to downhole hardware operations.

e. Could not use any fluid or gas chip flush due to weight limitations of the mission. The gas or liquid chip flush moves the chips to the surface where they are collected. Liquids could not be employed on the lunar surface due to the vacuum, subsurface cold, and surface heat effects even if there were no weight restraint. Earlier studies have indicated that the volume of compressed gas required to evacuate all chips from a 100-ft hole would require a gas container weight exceeding the overall lunar drill weight budget by a factor of 2 to 3. Methods would have to be provided which would move the chips to the bit OD periphery where they would be moved up by the auger and removed with the core to a collection point. The shorter the auger, the higher the potential of augering the chips and the less power required.

f. Had to drill with a rotary diamond bit which had no lubrication or external cooling. Since the lunar environments forbade the use of liquid or gas chip flushes which would also act as a diamond coolant and since the industrial diamond tool manufacturers followed the philosophy that diamonds must be cooled as they cut, a bit cooling system had to be devised to cool the diamonds from the inside of the bit. The bit coolant system had to include a heat exchanger, connected by a hose to a rotary joint so that the condensed coolant could run down to the bit through a rotary joint, chuck, and through tubes built with the drill rods and outer core barrel to an annulus in the bit crown. Return paths for the coolant vapor paralleled the coolant routes. A rather complex valving system had to be devised to prevent significant losses of coolant to the lunar vacuum during the drill string additions and inner core barrel retrieval activities. The discovery that diamonds could drill without a coolant or a lubricant eliminated these design approaches, thereby eased the number of manual operations to be performed by the astronauts.

g. Had to prevent overburden cave-in. The casing of the hole to prevent overburden cave-in would have to be limited due to the lunar drill weight restraints. Since it was expected that only the immediate lunar subsurface would be unconsolidated enough to result in cave-ins, the casing was limited arbitrarily to the depth of 5 feet.

h. Had to complete a 100-foot hole and recover core within the lunar mission schedule limits.

A preliminary analysis showed it would take approximately 40 hours to install, drill a 100 foot hole in dry rock, and collect samples using the wireline techniques which was commensurate with a lunar module mission time frame. No problems of a nature which would make a lunar drill unfeasible have come to light during the Westinghouse studies of the lunar drilling problems.

3.2 DESIGN PHILOSOPHY

In the design of the Moderate Depth Lunar Drill, the limitations of the spacesuited astronaut was one of the major tradeoff areas considered. The physical problems encountered by the Gemini astronauts during extra-vehicular activity indicated that a maximum degree of automation should be provided to lighten the astronaut workload. However, the overall drill system weight had to be limited to 200 pounds. A compromise had to be made between automation and the resultant lightening of the astronaut work-load on one hand and weight saving on the other. It was believed to be more important during the initial development to demonstrate the feasibility of the overall approach than to design maximum automation into the equipment at the expense of time, weight, and additional funds. Therefore, automatic control and protection devices were made a part of the system, but full automation was not incorporated.

Due to the limited time and funds available for the development of the engineering model and the many areas in which significant research and development were necessary, it was not possible to carry out an extensive component and subsystem development testing program. The results of previous programs in such areas as drilling, solid lubricants, and sealed motors for vacuum application were drawn upon heavily as background for the engineering model. Background obtained from these programs and experiences indicated a high probability of success in these development areas.

The one area in which no success had been experienced previously was that of dry (no coolant or lubricant external to the bit) diamond drilling. As a result, this subject received considerable attention. To date, it has been demonstrated that a dry diamond bit will have a life in excess of 100 feet in a dry Dresser basalt.

From the overall systems viewpoint, the decision, not to enter into an extensive research program but to extrapolate the results of other programs to the particular problems to extrapolate the results of other programs to the particular problems to be encountered in the lunar drill, resulted in subsystem and component failure during the various systems test. Some failures were related to quality control problems rather than the design, and some were related to the learning process in the development of dry diamond drilling technology.

4. SYSTEM DESCRIPTION

Figure 4-1 shows the contract NAS 8-20547 configuration with the rotary joint removed and setting to the left of the inner core barrel which is being pulled from the interior of the initial 5-foot section augered outer core barrel by the overshot/wireline/hoist system.

Figure 4-2 shows the assembled engineering model of the lunar drill in its Contract NAS 8-26487 configuration less the overshot, the sealed motor and its heat exchanger system, and the hoist support frame. The tray, shown below the gearbox, was added in the laboratory to catch any oil dripping from the gear box. A very small leakage occurred initially before the sealing of the numerous entries into the gearbox was made effective. The initial 5-foot section of the outer core barrel and the bit are shown in place.

It is intended that the flight model would fasten to the side of the lunar module in a similar fashion to that shown.

The drill frame, drive motor, gearbox, ball screws, and chuck form an assembly which folds for transport. Figures 4-3 and 4-4 demonstrate the method of folding and erecting the lunar drill using the drill mock up. The downhole hardware was to be packaged in groups of several parts each which would be off loaded from the lunar module in the order of use. Each group would be of a mass commensurate with the astronaut's physical capabilities on the lunar surface and the lunar module cargo space.

Each of the sketches (figures 4-5, 4-6, and 4-7) shows a sealed motor with a closed loop cooling system consisting of hoses, external pump, and a heat exchanger. The external pump was added when it became apparent that the pump internal to the motor was ineffective. Since the motor cooling system design was not suitable, an air-cooled motor was supplied for system test purposes and appears in figure 4-5.

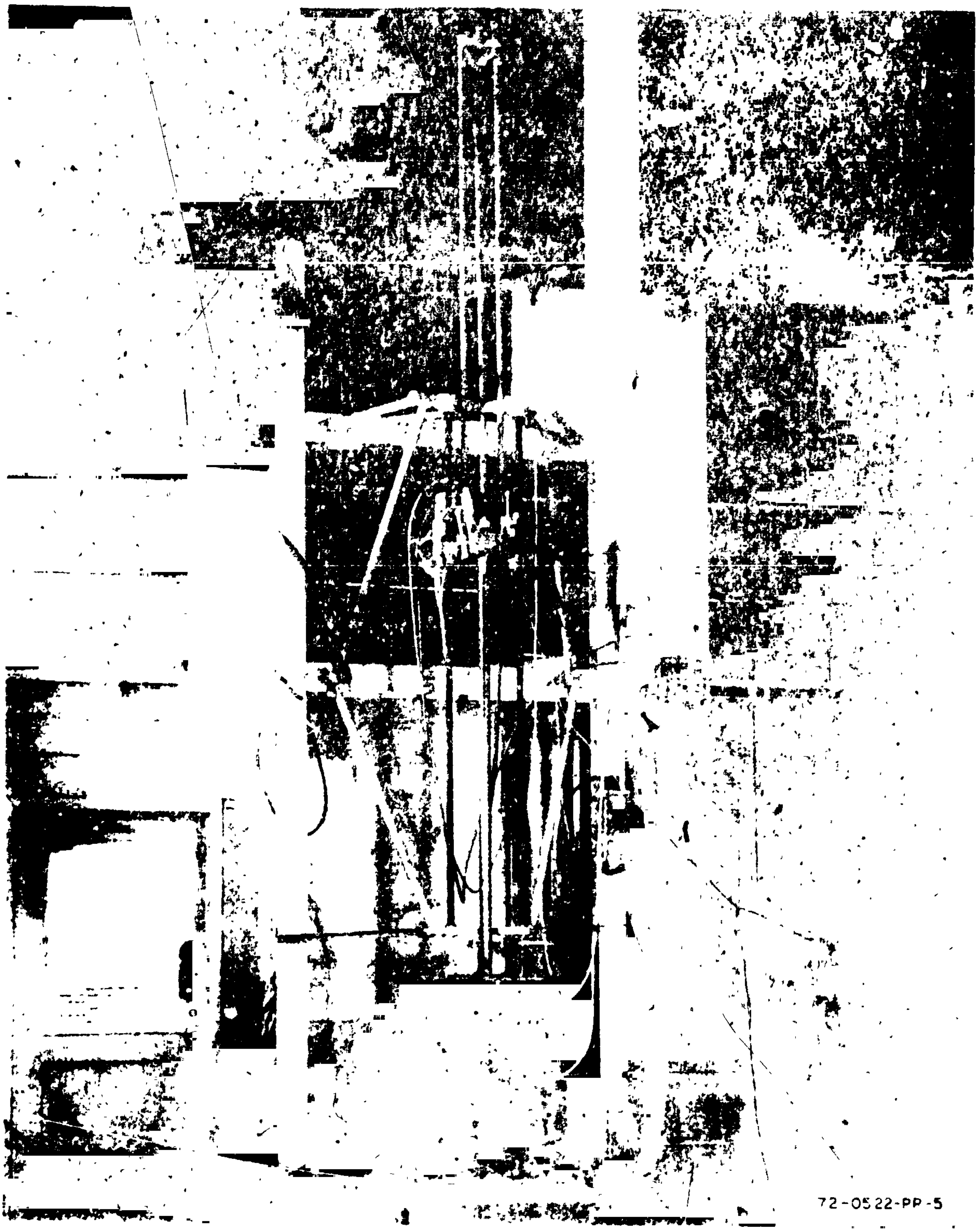

Figure 4-1. Contract NAS 8-20547 Lunar Drill Configuration

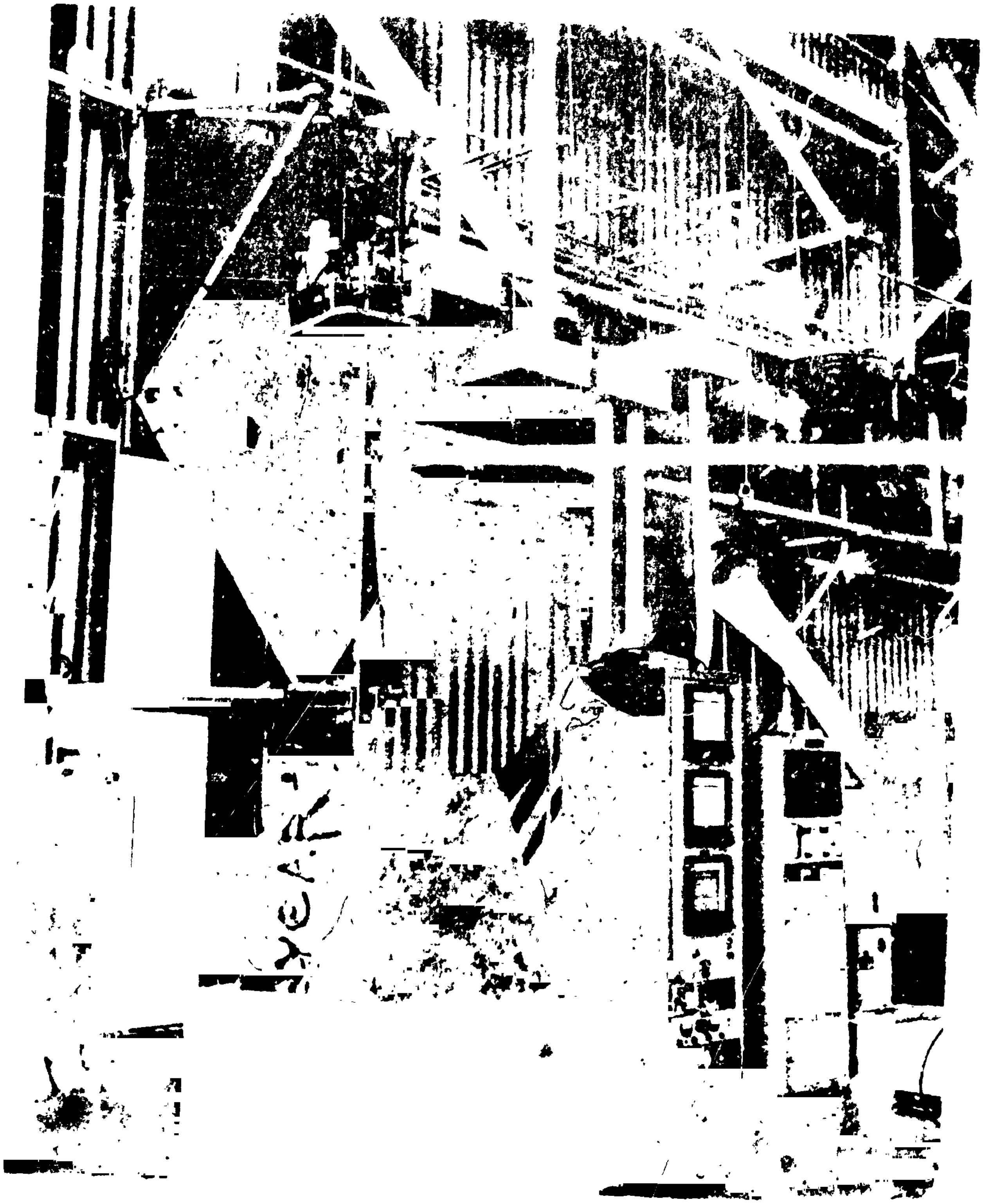

Figure 4-2. Contract NAS 8-20845 Lunar Drill Configuration

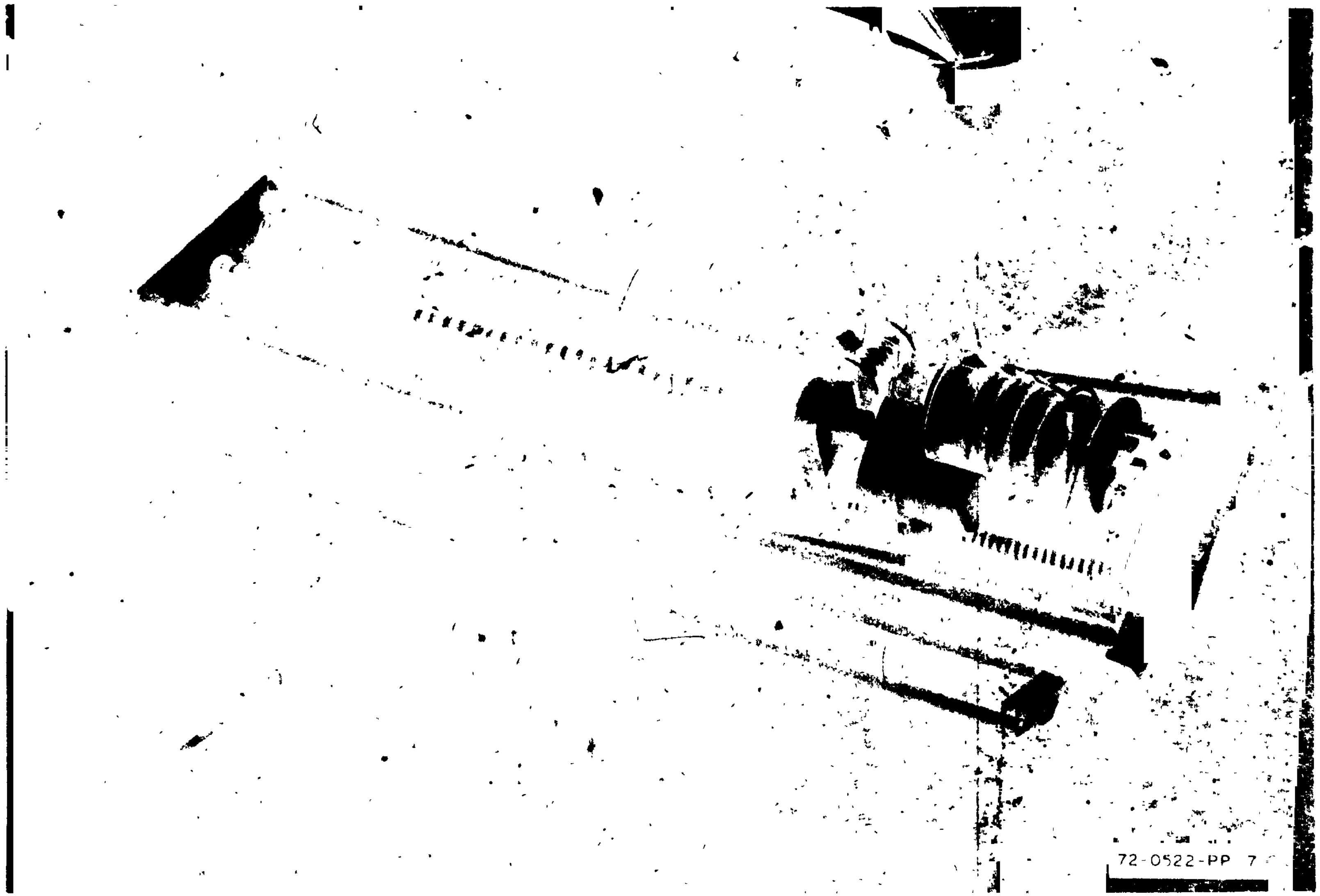

Figure 4-3. Contract NAS 8-20547 Lunar Drill Mockup Demonstrating Drill Folded for Transport

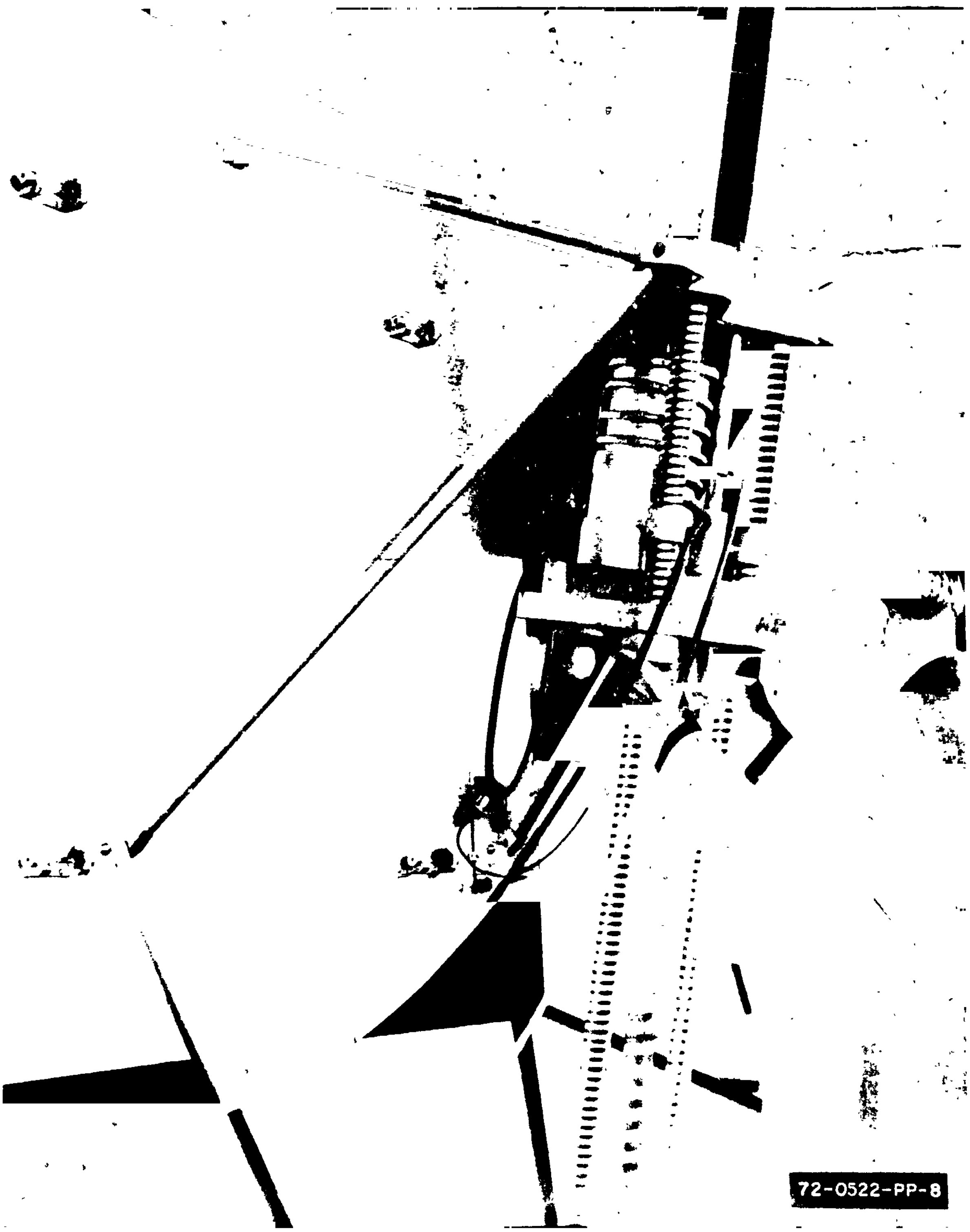

Figure 4-4. Lunar Drill Mockup Being Erected

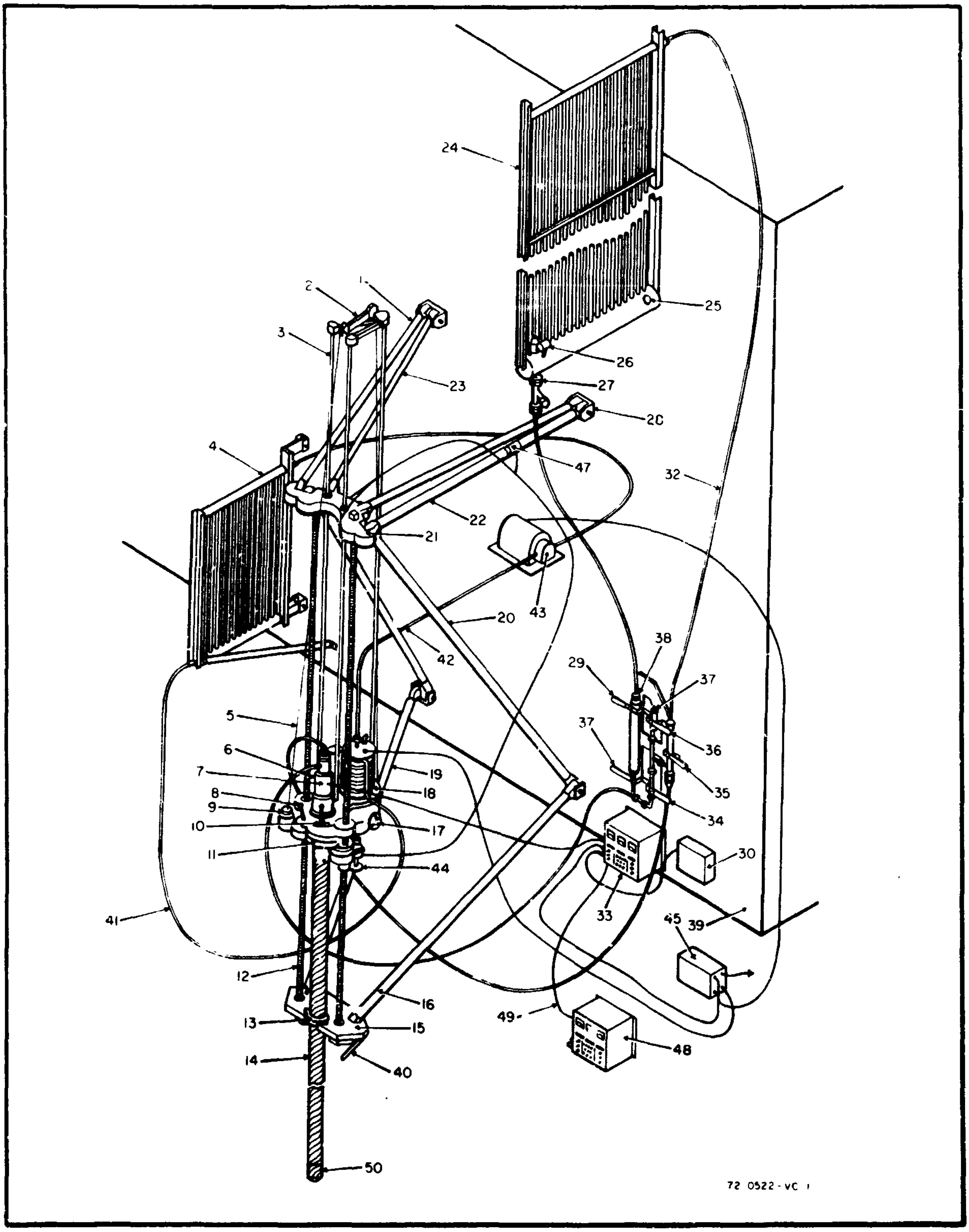

Figure 4-5. Lunar Drill, Engineering Model, Contra^t NAS 8-20547 Configuration

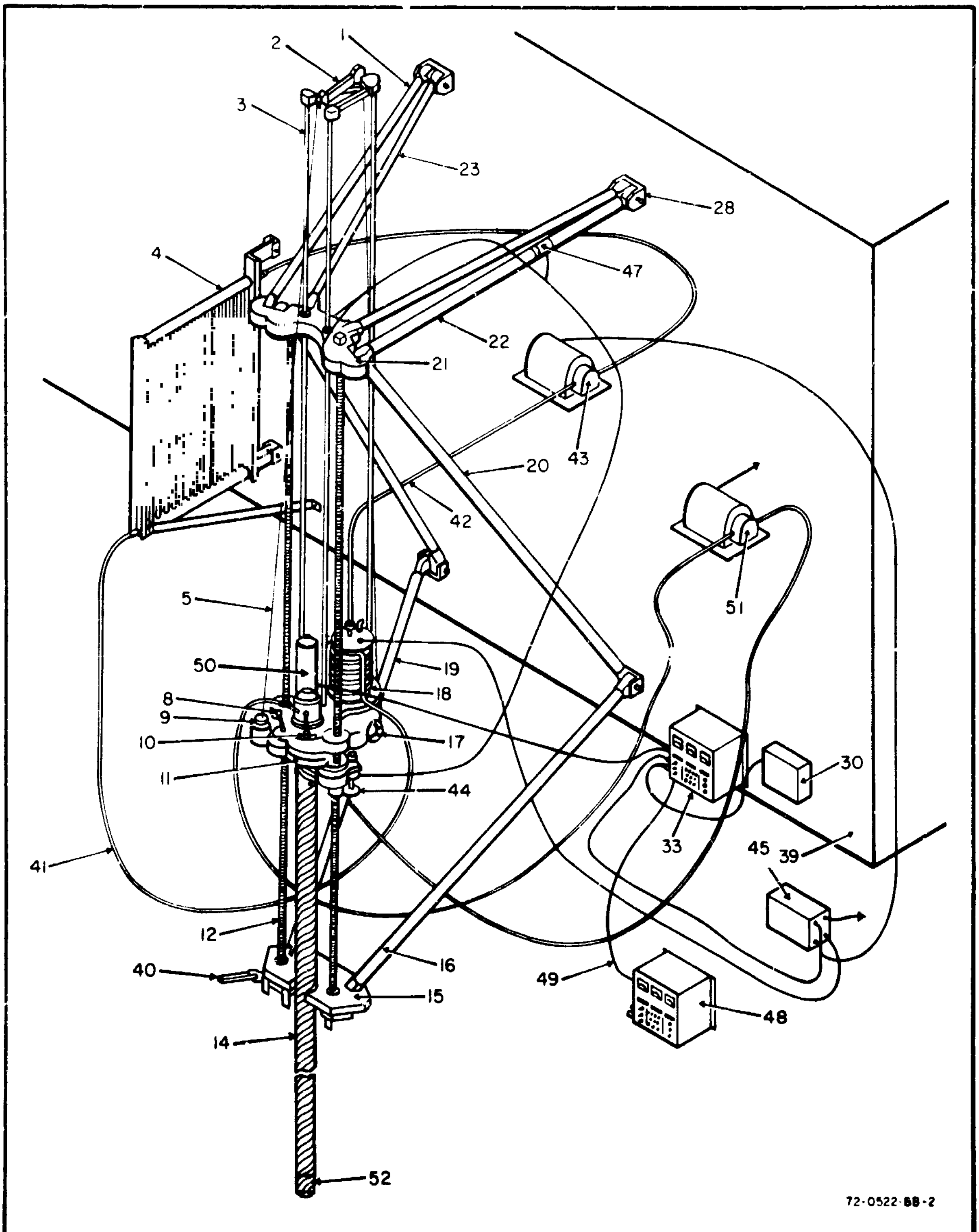

Figure 4-6. Lunar Drill, Engineering Model, Contract NAS 8-20845 Configuration

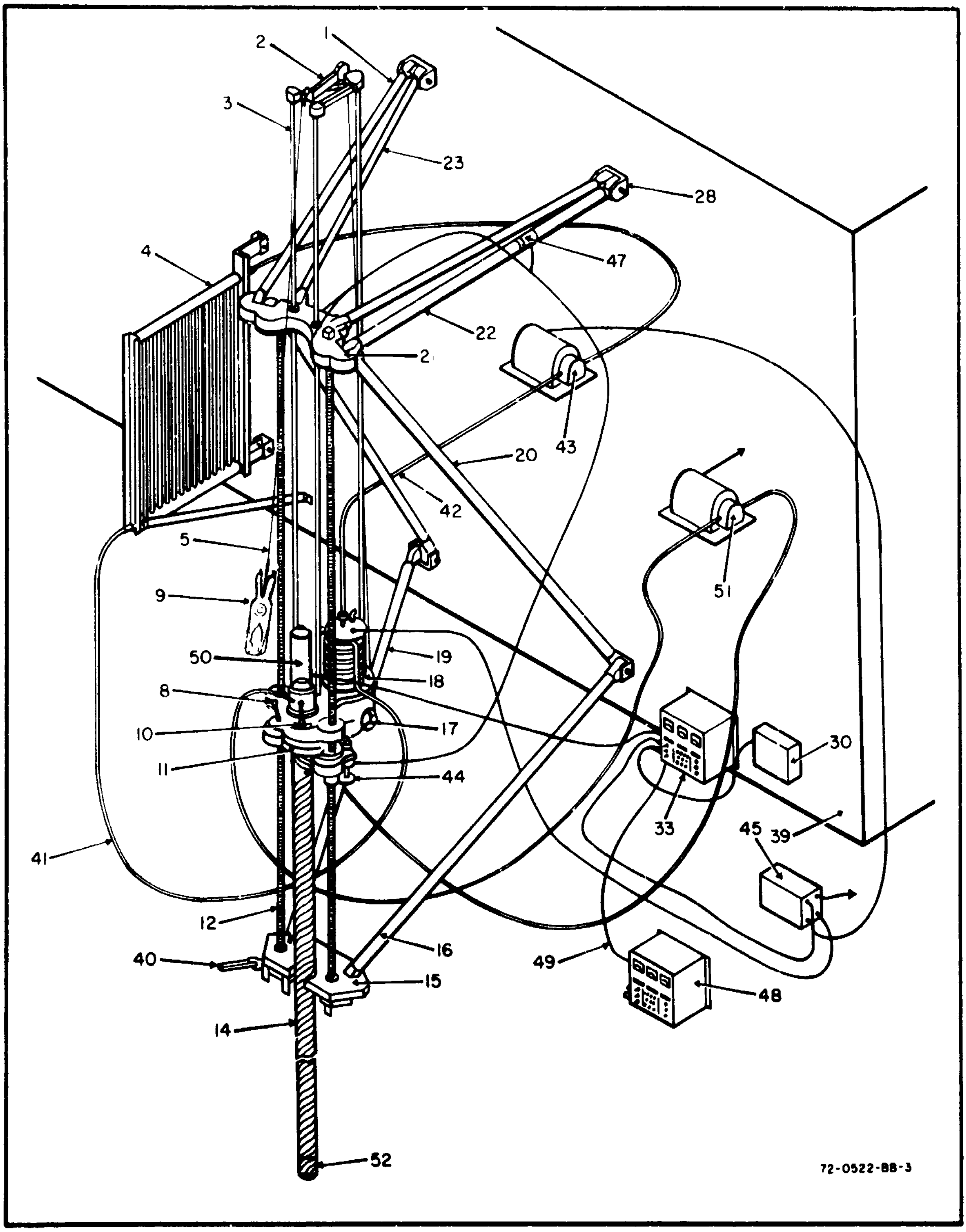

Figure 4-7. Lunar Drill, Engineering Model, Contract NAS 8-26487 Configuration

Under Contract NAS 8-20547 the gearbox had a neutral position and two rotational speeds for driving the drill string. During Contract NAS 8-20345, the gearbox was redesigned to change the rotational speed from 1,000 rpm to 504 rpm. The new gear design and the gearbox configuration required that the lower rotational speed be eliminated. Consequently, there is only a "neutral" and "high" gear shift position. The second gear shift lever which controlled the powering of the hoist or the feed train was unchanged. To avoid a potential reliability problem and to improve the up-stroke speed of the drive mechanism, a reversible small motor was substituted for the back-to-back hysteresis clutches which controlled the speed of the hoist and feed operations.

The drill string is connected by a chuck to the bull gear of the drive mechanism. A 100-foot drill string consists of seventeen 5-foot lengths of drill rod and three 5-foot sections of augered outer core barrel and a bit. Internal to the three-sectioned auger core barrel is a three-sectioned inner barrel. The upper two sections are designed to hold the chips being cut. The bottom 5-foot section has the dual purpose of containing the core and of breaking the core if necessary. The core breaking mechanism (the core lifter) is a device which wedges against the core when the nonrotating drill string is raised slightly. Additional vertical movement of the drill string applies tension to the core and breaks it.

The inner core barrel is locked to the rotating outer barrel, but is able to remain stationary with respect to the rotating outer barrel when drilling by means of a bearing in the locking mechanism. The inner barrel/chip basket assembly is removed by means of a overshot which is attached to the wireline (the hoist cable). The overshot is lowered down to and locks to the inner barrel assembly. Tension, applied through the wireline, unlatches the inner core barrel assembly from the outer barrel. Then, the inner barrel assembly is raised to the surface where the three 5-foot sections are uncoupled in turn and emptied. The procedure is reversed, and when the empty inner core barrel assembly is firmly locked in place down hole, the drilling can begin again.

The three 5-foot augered outer barrels are fastened together in turn, as the drilling progresses. The chips are moved from the bit OD by means of the auger flights up to the surface until 14-1/2 feet of hole is drilled. Then they are moved inside to the chip basket portion of the inner core barrel through a window especially designed to direct the chips inwardly. Any chips getting by the chip entrance windows are driven back by a section of reversed augers. The chip stream enters the chip basket through a vaned entrance section which chops the stream to prevent bridging inside the chip basket.

Under Contract NAS 8-20547, the bit was thought to need cooling. Since an external coolant or lubricant was not feasible in the lunar environment, an internal bit cooling system was developed. The closed loop cooling system consisted of radiator, a valving system for preventing coolant loss during drill string additions or core retrieval, hoses, a rotary joint for transferring coolant to and from the rotating drill string, and coolant and vapor passages in the chuck, adapter, drill rods, and core barrel. The bit had an internal manifold which permitted the coolant to remove heat from the bit crown. It was felt essential at that point in the development to keep a constant monitor on the bit thermal level. A thermistor was embedded in the bit matrix and power to it and signals from it was passed by leads through contacts at every drill string joint to the rotary joint. A signal bridge and rotary transformer passed the signal to the control indicator via signal conditioner circuitry.

The bit coolant system, the bit thermal sensing systems, the passages in the drill string component and bit, the valving system, and the radiator became obsolete when it was discovered that the diamond bit could drill dry without cooling. Contract NAS 8-20845 and NAS 8-26487 configurations (figures 4-6 and 4-7) reflect these changes.

The Contract NAS 8-20547 configuration employed a solid lubrication system. The life design objective for this configuration was 160 hours. However, since it was expected that the laboratory test and the field test probably would exceed the life objective by several times, the solid lubricant system was removed and a forced oil system was substituted during Contract NAS 8-20845. This change is reflected in figures 4-6 and 4-7.

Contract NAS 8-26487 provided a modified version of the Longyear AQ overshot as a replacement for the magnetic overshot of Contracts NAS 8-20547 and NAS 8-20845. With this design change, the overshot holder and the existing hoist frame became obsolete. Although the hoist frame is still shown in figure 4-7, it will have to be modified by increasing its height and strength in the future development period. This will accommodate the increased length of the overshot utilized during Contract NAS 8-20845 as well as an inner core barrel section.

Under Contract NAS 8-20547, the control and protection unit was designed to receive bit temperature, thrust feed rate, axial limit, gear position, and support structure vibration signals to maintain automatic control of the drilling operation and to provide protection against damage. Visual fault and operating condition indications were provided by indicator lamps. Manual control was also provided. A remote control, when energized, could control the drill up to 100 feet from the drill site. Although the control worked well during Contract NAS 8-20547 in all modes, it was limited to a maximum thrust of 400 pounds by the circuitry. The Contract NAS 8-20845 study results indicated that the thrust upper limit should be approximately 2,000 pounds. The thrust circuit redesign was not funded in either Contract NAS 8-20845 or Contract NAS 8-26487. The overall control was operated on "manual" with the thrust being applied through a separate circuit employing a manual control. The bit temperature meter and indicator are no longer of use since the bit temperature is no longer sensed.

A motor starter was provided to limit motor power input to the gearbox, and a signal conditioner was utilized to convert the sensor signals to an appropriate form for control operation under Contract NAS 8-20547. There have been no design changes in these units.

CONTRACT NAS 8-20547 KEY SHEET

Item	Description	Drawing Number
1	Upper truss	611R562G01
2	Hoist platform	611R628
3	Hoist support frame	511R881G01
4	Motor coolant radiator	332D306 (use with AED 976J551 motor only)
5	Hoist cable	WE1306
6	Rotary joint anti-rotational device	6614DS04
7	Rotary joint	WE1191
8	Feed-Hoist gearshift lever	WB1313
9	Overshot in overshot-rotary joint basket	6617DS01
10	Low-Neutral-High gearshift lever	WB1214
11	Gearbox	WG1229
12	Feed screw	WB1091
13	Lower platform bushing	6612DS09
14	Outer core barrel assembly	WE1310, WE1313, WE1316
15	Lower platform	611R555H01
16	Brace	611R558G01
17	Hoist	WD1237
18	Drill motor	AED976J551, AMF6615DS02
19	Brace	611R558G02
20	Lower truss	611R561G02
21	Upper platform	611R564H01
22	Upper truss	611R564G02
23	Upper truss	611R627G02
24	Bit cooling radiator	608J272H07
25	Pressure gauge fitting	608J272H10

CONTRACT NAS 8-20547 KEY SHEET (Continued)

Item	Description	Drawing Number
26	Air eliminator	G08J272H10
27	Water flexline fitting	G08J272H08
28	Frame mounting bracket	511R855
29	Valve A - water metering valve	915F237
30	Signal conditioner	6618DS01
31	Valve B - water control valve	915F237
32	Steam flexline	915F237
33	On site control	915F237
34	Valve C - vapor collector valve	915F237
35	Valve E - steam valve	915F237
36	Valve D - vent valve	915F237
37	Vapor vent	915F237
38	Valve assembly	332D515
39	Simulated LEM	
40	Foot clamp	6610WH13
41	Coolant flexline - motor to radiator	332D306 (use with AED 976J551 motor only)
42	Coolant flexline - pump to motor	332D306 (use with AED 976J551 motor only)
43	Motor coolant pump	(use with AED 976J551 motor only)
44	Feed rate sensor assembly	6619WH04
45	Starter	661WH44 (AMF 28 VDC motor) 336D050 (AEO 100 VDC motor)
46	Starter-on site control cable	(Separate with 336D050 starter) (Part of cable harness 336D050 starter)

CONTRACT NAS 8-20547 KEY SHEET (Continued)

Item	Description	Drawing Number
47	Thrust sensor	
48	Remote control	915F236
49	Remote-on site control cable	
50	Bit	8267

CONTRACT NAS 8-20845 KEY SHEET

Item	Description	Drawing Number
1	Upper truss	611R562G01
2	Hoist platform	611R628
3	Hoist support frame	511R881G01
4	Motor coolant radiator	332D306 (use with AED 976J551 motor only)
5	Hoist cable	WE1306
8	Feed-hoist gearshift lever	WB1313
10	Low-neutral-high gearshift lever	WB1214
11	Gearbox	WG1229
12	Feed screw	WB1091
14	Core barrel assembly	WF2104
15	Lower platform	611R555H01
16	Brace	611R558G01
17	Hoist	WD1237
18	Drill motor	AED 976J551 (sealed) or AMF 6615DS02 (air cooled)
19	Brace	611R558G02
20	Lower truss	611R561G02
21	Upper platform	611R564H01
22	Upper truss	611R564G02
23	Torque brace	611R627G01
28	Frame mounting bracket	511R855
30	Signal conditioner	6618DS01
33	On site control	915F237
39	Simulated LEM	
40	Foot clamp	E90M04686

CONTRACT NAS 8-20845 KEY SHEET (Continued)

Item	Description	Drawing Number
41	Coolant flexline - motor to radiator	332D306 (use with AED 976J551 motor only)
42	Coolant flexline - pump to motor	332D306
43	Motor coolant pump	(use with AED 976J551 motor only)
44	Feed rate sensor assembly	6619WH04
45	Starter	6610WH44 (AMF 28 VDC motor) 336D050 (AEO 100 VDC motor)
46	Starter-on site control cable	(Separate with 336D050 starter) (Part of cable harness 336D050 starter)
47	Thrust sensor	—
48	Remote control	915F236
49	Remote-on site control cable	
50	Hysteresis clutch assembly	—
51	Gearbox lubricant pump	—
52	Diamond Bit	NAS-54-W-NAS-54-16A

CONTRACT NAS 8-26487 KEY SHEET

Item	Description	Drawing Number
1	Upper truss	611R562G01
2	Hoist platform	611R628 (must be modified)
3	Hoist support frame	511R881G01
4	Motor coolant radiator	332D306 (use with AED 976J551 motor only)
5	Hoist cable	WE1306
8	Feed-hoist gearshift lever	WB1313
9	Overshot	Long gear AQ Overshot assembly 26604/W104RS
10	Low-neutral-high gearshift lever	WB1214
11	Gearbox	WG1229
12	Feed screw	WB1091
13	Lower platform bushing	6612DS09
14	Core barrel assembly	WF2104 modified by HDP W101RS, W102RS and W103RS
15	Lower platform	611R555H01
16	Brace	611R558G01
17	Hoist	WD1237
18	Drill motor	AED 976J551, AMF 6615DS02
19	Brace	611R558G02
20	Lower truss	611R561G02
21	Upper platform	611R564H01
22	Upper truss	611R564G02
23	Torque brace	611R627G01
28	Frame mounting bracket	511R855
30	Signal conditioner	6618DS01

CONTRACT NAS 8-26487 KEY SHEET (Continued)

Item	Description	Drawing Number
33	On site control	915F237
39	Simulated LEM	
40	Foot clamp	E90M04686
41	Coolant flexline - motor to radiator	332D306 (use with AED 976J551 motor only)
42	Coolant Flexline - pump to motor	332D306 (use with AED 976J551 motor only)
43	Motor coolant pump	(use with AED 976J551 motor only)
44	Feed rate sensor assembly	6619WH04
45	Starter	6610WH44 (AMF 28 VDC motor) 336D050 (AEO 100 VDC motor)
46	Starter-on site control cable	(Separate with 336D050 starter) (Part of cable harness 336D050 starter)
47	Thrust sensor	
48	Remote control	915F236
49	Remote-on site control cable	
50	Feed rate motor	Globe Industries 166A100-8/shaft WD1205
51	Gearbox lubricant pump	—
52	Diamond Bit	NAS-SY-W-NAS-SY-16A

5. SYSTEM COMPONENT DEVELOPMENT

5.1 BIT DEVELOPMENT

Although the principle of core drilling using gem stones and abrasive powders was evolved in ancient Egyptian times, it was not until the 1860's that the first rotary diamond drill using an annular ring set with diamonds was employed. By the late 1880's, steam-driven rotary diamond drills were in regular use.

The bits originally were set with carbonado or black diamonds found in South America. By the 1930's, these diamonds had become scarce and so high priced that South African Bortz diamonds were utilized. The method of making a diamond crown progressed from setting the diamonds in predrilled holes in a metal crown and held in place by metal caulking, through casting metal around the stones set in a mold, to a matrix of powdered metals held together by a metal infiltrant formed over Bortz diamonds set in a mold.

5.1.1 Contract NAS 8-20547

There were several rules of thumb which were industry guides for the design of rotary diamond bits at the beginning of contract NAS 8-20547.

- Diamonds required a coolant and a lubricant to drill rock.
- Use smaller and greater numbers of stones when drilling harder rock.
- Octahedrons were the better stones for drilling.
- Thrust per stone should be from 4 to 32 pounds/stone depending upon the authority.

- Numerous stone patterns, bit shapes, water course arrangements had been touted as being optimum depending upon the type of formation being drilled. Many contractors had their favorite designs and each bit manufacturer had his product design preferences. Some of the designs were based upon experience and some were based upon conjecture or manufacturing expediencies.
- Diamonds set in a snow plow spiral pattern were instrumental in moving the chips to the bit OD periphery.

Since there was no published record of a successful attempt to drill with a dry rotary diamond drill, it was necessary to initially evaluate the problems that exist with commercial drilling bits and then to design a development program based on the state-of-the-art knowledge. Since the contract covered a relatively short term, it was decided to initiate immediately both an empirical and an analytical program.

Commercial experience has shown that prompt chip removal from the cutting area is critical, since the bit binds and overheats if this is not accomplished. An analytical effort was undertaken at Westinghouse as well as at Arthur D. Little, Inc., to determine theoretically the cutting mechanisms involved, the fraction of the heat remaining in the rock, the amount that could be carried away as chips, and the amount that is transmitted to the bit.

Simultaneously, empirical efforts were initiated to determine the feasibility of drilling dry if chips could be removed, the design of auger flights to carry chips up and out of the hole, and the optimum design of the diamond bits to assist in the removal of the chips and to prolong the bit life.

The analytical effort, which paralleled the experimental work, drew heavily on the experimental results for guidance and verification. It can be shown on the basis of this work that approximately 80 percent of the total heat generated in drilling remains in the chips. Part of the residual heat remains in the rock and only a small portion of it is actually transmitted to the bit. It then follows that, if the chips can be quickly removed from the cutting area, the bit cooling required will be minimized. This analysis has led to the conclusion that if the chips could be removed, there was a reasonable possibility that dry drilling could be accomplished with no bit cooling.

By 1 December 1965, the feasibility of dry diamond drilling in ultra-high vacuum had been demonstrated by drilling approximately 6 inches into a basalt rock. The drilling was intermittent, allowing the bit to cool after every 30 seconds of drilling. Chip removal was excellent and no bit damage resulted.

Following the demonstration of feasibility, the bit tests continued with appropriate instrumentation which allowed the determination of matrix temperature, rpm, thrust, torque, penetration rate, and calorimetric measurements on specially designed bits. Continued study of the problems of diamond setting resulted in a general improvement in diamond bit design.

In the course of the experimental effort, 34 diamond bits were manufactured and tested. Table 2.1 of the NAS 8-20547 Final Report summarizes the tests run and the results obtained.

One of these bits drilled 123 inches in basalt while being internally water cooled. The drill system, being used for the test, limited the maximum stroke length to approximately 8 inches. If the bit could have been permitted to cut in 5-foot strokes, as the lunar drill design would have permitted, it is believed that the total depth drilled would have been much greater than the achieved life.

An average rotational speed of 1,000 rpm, thrusts of 4 pounds/face stone and a water flow of 3 gallons/minute as an internal bit coolant, which removed approximately 500 watts of heat from the bit, were the parameters used. The penetration rate varied from 3 inches/minute to 1/4 inch/minute with torques varying up to 10 pound-feet.

The bit design based upon the 123-inch-life bit design and delivered as part of the contract is shown in figures 5-1 and 5-2. The face diamonds are oriented octahedron stones exposed approximately 0.010 inch above the matrix. The ID and OD gage stones are combination octohedron and dodecahedron crystal structures

Figure 5-1. Contract NAS8-20547 Diamond Bit Pattern

Figure 5-2. Contract NAS8-20547 Bit Construction

The diamonds were set in a "snow plow" fashion, and five chip channels were designed into the bit face to permit easier flow of the chips to the OD. These joined the auger section on the bit shank which had five auger flights set at a 35-degree auger angle. One drill bit was used to drill dry into basalt. No internal coolant was used and drilling progressed normally to 22 inches where the bit failed mechanically. Inspection of the bit showed only minor chipping of the face diamonds and normal wear on the remainder. The crown mechanical failure occurred due to the seizing of the bit as a result of a chip binding problem.

5.1.2 Contract NAS 8-20845

The failure to reach the 100-foot bit life in basalt and the continu quality problems indicated the need for further bit development. A major portion of contract NAS 8-20845 was dedicated to bit development and research. The various areas of study and results follow.

5.1.2.1 Diamond Bit Study

The Diamond Bit Research Study has, as its goal, to provide an optimized bit design which would reach the minimum objective of drilling 100 feet beneath the moon's surface.

Through the design and testing of 53 bits, 14 bit design variables and 6 operational variables were studied. The bit variables were:

- Class of diamond
- Crystal form of diamond
- Size of diamond
- Exposure of diamond
- Orientation of diamond
- Diamond pattern
- Reaming diamong pattersn (ID and OD)
- Crown contour
- Chip release areas
- Auger entry

- Matrix material
- Auger angle
- Auger depth
- Auger-hole clearance.

The operational variables were:

- Thrust
- Revolutions/minute
- Bit break-in
- Chatter
- Penetration/revolution
- Test material variations.

Many of the variables were interdependent, making it very difficult to achieve an optimized design.

At the beginning of this study, the ultra-careful selection of the diamond crystals was felt to be of primary importance. If identical coring bits could be manufactured, one variable at a time could be tested.

5.1.2.1.1 Class of Diamond. - The quality of the stones employed, of necessity, had to be as high and as uniform as possible to avoid problems associated with diamond failure. To determine the suitability of commercially sorted high grade diamonds, a parcel of 100 carats of 30/carat AAA grade diamonds was obtained for examination. A 30X magnification visual examination showed so many hairline flaws and other surface imperfections that drill boart diamonds of this grade were considered unsatisfactory. A parcel of 100 carats of South African boart 30/carat AAAA grade was therefore obtained. This grade is defined as: AAAA - a letter symbol to designate quality of diamonds better than AAA grade; such diamonds also may be designated by symbols or terms as: Creams, 4A, Quadruple A, Special, Special Rounds. Also called Gem, Gem Grade. 30X magnification indicated that this quality of diamond was relatively free of surface and subsurface imperfections. Those diamonds, which had questionable indications, were rejected at the manufacturer's location.

Halfway through the program, the AAAA boart, in the size range required, became less readily available. Brown Premier dodecahedrons from the De Beers Premier Mine were used for the last half of the program and appeared to perform equally well.

5.1.2.1.2 Crystal Form of Diamond. - The basic crystal form of the diamonds was considered, and both octahedron and dodecahedron forms were selected. The cubic forms were not available in the quantities and sizes required.

Experience derived from testing many bits indicated that dodecahedron diamonds appeared to hold up better under dry drilling conditions. There was less diamond fracture and wear under the conditions of slight chatter and the high individual stone loading required to obtain the maximum bit life.

5.1.2.1.3 Selection of Diamonds. - Specifications and procedures for the selection of the test diamonds were prepared. The diamonds were to be presorted and packaged according to the crystal form. The size of the diamond was to be within ±1 of the normal size, e.g. for 30/carat diamonds the weight was to be from 29 to 31/carat. The surface and internal quality acceptance of the diamonds was to be made by the research personnel.

Each diamond crystal was mounted in a holding fixture and viewed through a toolmaker's microscope at 30X magnification to select the point appearing the most perfect geometrically. Linear and angular dimensions were recorded and the point was marked with a red dye to enable the diamond setter to identify the point to be set in the mold. The crystal was then placed in a vial coded to tie it to its recorded data.

Dimensional means and a series of tolerances ranging from ±0.001 inch to ±0.004 inch were established from the measurement data using a computer. It was found that setting a dimensional tolerance less than ±0.004 inch resulted in too few crystals being available, and the larger tolerance was set as a standard. With this standard, 50 percent of the 20/carat, 65 to 75 percent of the 30/carat, and 95 percent of the 50/carat stones could be used.

Further study indicated that only those dimensions which are directly related to the protrusion of the diamond above the matrix appeared of value. In the latter days of the program it was found feasible to drop even these measurements although the visual examination, diamond weight tolerances and crystal form selections were maintained.

5.1.2.1.4 Size of Diamond. - Although the rule of thumb in the drilling industry is "the harder the rock, the smaller the stone," the problem of possible chip blockage, due to the small rock-matrix interface volume which results from the slight diamond protrusion of smaller diamonds, suggested the use of larger stones than normal.

To cover a range of diamond sizes which might prove acceptable for the testing program, 15/carat, 20/carat, 30/carat, and 50/carat stones of the AAAA quality were procured and tested in bits. The 20 per carat stones gave better life than the 30 and 50 per carat stones. The difference in results appeared to be due to changes in bit design such as stone protrusion from the bit face. Only one bit was made using 15 diamonds per carat, and it performed poorly. The short life appeared to be caused by the stones' planes and points tending to be more rounded than the smaller weight stones. The 400-pound permissible thrust was not high enough to cause stones to penetrate into the rock. The under thrust caused the diamonds to polish rather than cut. The larger stones were not tried again, although their use under a higher thrust regime probably would be satisfactory.

5.1.2.1.5 Exposure of the Diamond. - Rock chips must be moved from the bit-rock interface quickly and efficiently to remove the heat resulting from the cutting operation, to prevent a mass of chips from filling up the matrix-rock interspace which would reduce the thrust applied to the diamonds, and to reduce diamond wear resulting from chip abrasion.

The majority of the chips must travel some distance across the bit face and must find their way to the OD periphery through the intervening diamonds in order to be released to the auger flights. Microscopic examination of the rock cutting particles indicated that the maximum chip size was approximately 0.007 inch x 0.0035 inch x 0.002 inch. If the chip turned in passing across the bit face contour, then the minimum passage height required was assumed to be 0.007 inch if no piling up or grinding of the chips was to occur.

The average diamond protrusion above the matrix was determined by optical comparator measurements. If a diamond bit is rotating at 500 rpm and penetrating at a rate of 4 inch/minute, the penetration per revolution would be approximately 0.008 inch. If two diamonds with the same protrusion follow the same track, the 0.008 inch penetration is divided between the two stones. Subtracting half of this figure from the average diamond protrusion would determine the average distance remaining between the rock face and the matrix for chip passage.

Approximately two-thirds of the diamond must be embedded in the powdered metal to firmly secure the crystal. The smaller the crystal, the less the physical exposure will be. For example, 50/carat diamonds will thus have less physical exposure than 20/carat crystals. In addition, if the diamonds are set at a predetermined negative rake, the greater the rake angle, the less the diamond protrusion will be above the matrix.

Longer bit life was obtained with greater diamond protrusion. Using 20/carat stones, the protrusion on similar bit designs was increased over that achieved with 30/carat diamonds from an approximate average of 0.008 inch to 0.015 inch. The greater protrusion was produced not only by setting the stones slightly less deep in the matrix, but also by changing the rake angle from a nominal 15 degrees to a nominal 4-1/2 degrees.

5.1.2.1.6 Diamond Orientation. - Scientists, through crystallography, have established that even though the bonds between all atoms of the diamond have equal strength, they are so distributed that there are more bonds in some layers or directions through the crystal than in others. This unequal directional distribution of bonds creates planes within the diamond which may vary in strength and resistance to abrasion. The planes which are more

C.2

resistant to abrasion for the several crystal forms have been delineated and are termed "hard vectors." "Orientation" is the term employed to describe setting the harder diamond structures as cutting surfaces to reduce the diamond wear losses and to increase the efficiency of the bit. Except for the cubic diamonds, the crystals are set at a negative rake angle to obtain the benefit of the harder structure.

Long and Slawson state the the negative angle of rake can be set practically from 6 to greater than 25 degrees to expose the harder diamond surface structure. Experience in the setting of many bits for commercial igneous rock drilling indicates that the practical limits of the rake angle could be from 0 to 15 degrees. In the lunar bit studies, a range of 4-1/2 to 15 degrees negative rake angles was employed to attempt to take advantage of the hard vector and at the same time obtain the desired greater diamond protrusion. The rake angles above 15 degrees were not explored, primarily due to the resultant reduction in diamond protrusion associated with embedding the stone adequately in the matrix. A nominal 4-1/2 to 7-1/2 degree negative rake appears to be an optimum range for the lunar design.

Setting the stone accurately depends upon the setter being experienced in identifying the harder surfaces and in being precise when positioning the stones. The high quality crystals and the carefully drilled and angled "pip" marks made the setting of the hard vector relatively easy. Despite the pip design and the care taken in setting the stones, the rake angle of the diamonds in the finished bit varied by as much as ±5 degrees from the nominal due to the variables introduced by the subsequent crown manufacturing processes. The actual angular tolerance could not be easily determined due to measurement difficulties.

5.1.2.1.7 Diamond Pattern. - The diamonds which do most of the cutting are the face stones (those on the bit face), and the periphery or gauge stones (those on the inside and outside shoulders of the bit crown).

The cutting diamonds are located on the crown by radial and angular dimensions. All diamonds on the same radius are said to be "in a line circle." The spacing of line circles must always be less than the width of the diamond at the matrix surface to prevent the matrix from contacting on the rock. If contact occurs, the matrix acts as a bearing surface and the bit will heat up and disintegrate quickly. For the first 19 bits tested, 10 to 12 line circles were utilized with spacings of approximately 0.030 inch between line circles and with 5 to 10 diamonds per line circle. Later, the design was altered from 11 line circles to one of 31 line circles. The previous design had 9 diamonds per line circle. By shifting three of these outward and three inward approximately 0.010 inch, two additional line circles were created for each existing one and the bite of each diamond for the same penetration rate was theoretically tripled. Due to the variation in diamond height and the shape of the point, the bite of each diamond was probably less than doubled. For example, with nine diamonds in a line circle, perhaps three stones, on the average, were actually working. With only three in a line circle, there were probably about one and half to two stones cutting on the average. If the number of diamonds in the bit is unchanged, then the line circles are spaced at only two-thirds of their previous spacing. Thus, the diamonds cut a narrower ridge of rock which probably offers somewhat less resistance to penetration by the diamond, and results in a higher rate of penetration. Under the same thrust, a bit with 31 line circles cut at 4.4 inch/minute whereas a bit with 11 line circles cut at a rate of 2.9 inch/ minute. The main significance was not the higher penetration rate per se but the 50 percent improvement in life which resulted. Since neither bit had fractured diamonds nor chatter, the difference was due apparently to the greater bite of the diamonds resulting from these changes. To show that the bite of the diamond was really the significant change, further tests were made in which the increase in bite was accomplished by changing the thrust. This had an even greater effect on bit life, substantiating the theory. The 31-line circle pattern setting was adopted.

Other than the change in number of line circles, no other pattern change was found to give significant results. In general, the pattern consisted of arranging the diamonds in a spiral fashion which was intended to sweep the chips outward. The effectiveness of these spirals could not be determined, since there are also large spaces between adjacent diamonds in the spiral and the dynamics of the chips as they break off at the diamond-rock interface are unknown. However, with any diamond pattern, there is a tendency to move chips outward due to centrifugal effects of rotation. On a few test bits which contained a larger than average number of diamonds, clear paths to the OD were interrupted by one or more stones. These stones appeared to slow the chip passage and/or direct the flow back toward the ID. Subsequent bit designs carefully avoided this arrangement.

The final bit pattern is configured as shown in figure 5-3.

5.1.2.1.8 Reaming Diamond Patterns. - ID and OD. - The ID and OD reaming stone patterns were varied over the number of bit designs made. The best arrangement appeared to be where the ID and OD stones were set in a linear fashion continuing the lines of diamonds formed by the face stone pattern.

5.1.2.1.9 Crown Contour. - Early in the NAS 8-20845 testing program, there were indications of cuttings being trapped at the ID and excessive wear of the octahedrons on the face compared to the peripheral dodecahedrons. The contour, similar to the 123 bit which had a 15-degree face angle, was maintained for the first six bits set with 30/carat diamonds. For each bit, attempts were made to control the fracture inducing vibration through variations in diamond layout and rake angle. Little improvement resulted. It was concluded that the ID radius did not give adequate support to the peripheral stones for either 20 or 30/carat diamonds.

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Figure 5-3. Contract NAS 8-20845 Optimized Bit Pattern

Another bit was manufactured, maintaining the same general contour, including the 15-degree face angle and OD radius used in its predecessors. The original 0.030-inch ID radius was increased to 0.050 inch, a change which resulted in a reduced but still unsatisfactory level of vibration and subsequent crystal damage. Chip trapping at the ID presented no problem.

Since it was felt that internal cooling was no longer necessary, the internal cooling passages in the crown were eliminated. The change in OD set size, which resulted, permitted a reduction of 0.076 inch in diamond crown kerf width. A review of test results up to this point suggested that a drastic change in the crown contour could be carried out to reduce vibration. The kerf width and crown change was incorporated in the next bit.

Test results substantiated that the new configuration, which approached a half-round face, was definitely a move in the right direction to reduce vibration. This contour approach was maintained for most of the bits remaining in the program.

The radius of the face contour on one bit was increased to provide a flatter surface for setting the diamonds so that the plane bisecting the crystal through the cutting plane and point could be made parallel to the vertical axis of the bit. The test results indicated that the contour contributed to excessive vibration. However, the method of diamond setting resulted in an improved diamond cutting action. It was determined subsequently that the majority of face diamonds could be set vertically on a 0.235-inch radius contour and still be embedded to an adequate depth in the matrix. All observations of the vibration level, penetration rate, effectiveness of chip release areas, track pattern, and particle movement indicated that this design change was a definite improvement. A 0.273-inch radius is used on the final bit contour design which has a wider kerf.

5.1.2.1.10 Chip Release Areas. - The original crown design provided for three chip release areas. These were raked back away from the direction of rotation by approximately 30 degrees. A theoretical analysis indicated that a 15-degree backward rake would be somewhat more effective. It was felt that additional areas would expedite the removal of rock particles and increase the overall bit efficiency. Three additional release ports, making a total of six, were incorporated in the crown design. Observation of the effect of this change during test runs indicated that chip ejection was accelerated. Based on these results, both 9 and 12 chip release areas were tried. The indications were that there was little difference in chip movement efficiency between the 6.9 and 12 release areas for the narrower kerf bit. In the wider kerf of the final bit design, 18 release ports appeared necessary to funnel the chips over the greater distance.

The advantage of having or not having release areas on the ID surface of the bit crown was investigated. The effect of not having the ID release areas had been tested on three bits. At that time, it was felt that these areas were detrimental to chip flow. Further study, on bits which contained ID release areas, tended to show that it was not the presence of the ID release areas which was detrimental to chip flow, but rather their configuration. It was observed that the channel of the release area appeared to be clogging with the larger rock particles, and a slight angular change to the channel walls was made and incorporated. Subsequent testing provied the change to be effective and resulted in an ID release area which was beneficial to chip removal.

5.1.2.1.11 Auger Entry. - Since chips are moved to the OD periphery of the bit by a variety of forces, they must fill up the interspace between the bit OD and ID of the hole to the level where they can enter the auger flights. To keep this level as low as possible, channels are provided in the bit OD as continuations of the chip release areas provided in the bit face and ID. Thus, if six chip release areas were provided in a bit, there would be two entries to each of the three augers. It is interesting to note that only the first two entries seem to fully function. There are some indications that chips also move up the paths between the OD and "kicker" stones to the augers when six or fewer auger entries are employed. The final design employs six entries/auger as continuations of the 18 face chip release areas found to be necessary for the smooth flow of chips across the bit face (figure 5-4).

5.1.2.1.12 Matrix Material. - The matrix material and the infiltrant used in the bits during contract NAS 8-20547 were proprietary alloys developed by the Christensen Diamond Products Company. Since the composition of the alloy was unknown, the Hoffman Diamond Products Company research personnel considered initially three powdered metals and an infiltrant which appeared to have potential based upon their earth drilling experience.

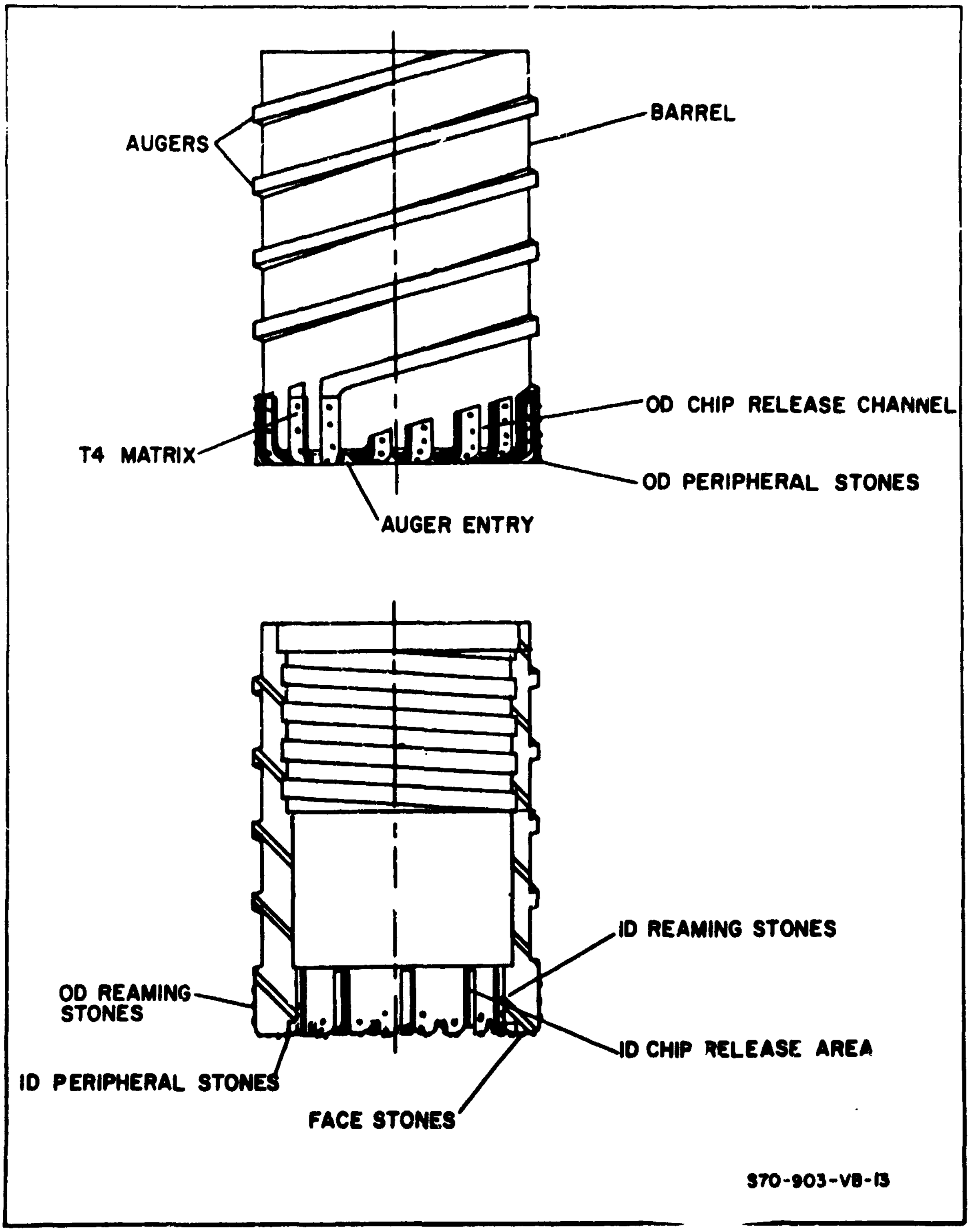

Figure 5-4. Lunar Bit Design

The three proprietary powdered metals, types 2, 3, and 4, were forwarded for testing to the Kennametal Corporation of Latrobe, Pa. This testing included matrix hardness, resistance to abrasion, and adhesion properties to Invar FM steel. The results of these tests showed that the type 4 metal would have the greatest potential.

Type 4 powdered metal was used in all test bits. In a few of the 30/carat and 10 line circle bits, there were some indications of matrix wear, but never enough to cause diamonds to pull out. There has been no apparent matrix wear on bits of the final design.

5.1.2.1.13 Thrust. - A 400-pound thrust restraint had been set at the start of the program. The optimum thrust/load bearing diamond had been suggested by several sources as being from 4 to 32 pounds per diamond. The average thrust/load bearing diamond in a bit was arbitrarily set by summing up the number of face diamonds and two-thirds of the OD and ID peripheral diamonds and dividing the total into the thrust applied to the bit. A considerable number of face and peripheral diamonds were thought to be needed to cut the kerf area on the early lunar drill bits. The number of diamonds utilized limited the thrust/diamond under the 400-pound thrust restraint. Diamond patterns were changed to reduce the number of diamonds using as "tradeoffs" the number of stones/line circle and the number of line circles.

In attempting to achieve a 7 to 12-pound load/diamond within the 400-pound limit, bits were designed which contained as few as 47 load bearing diamonds. These bits yielded no information due to excessive chatter which shattered the crystals. Later, the more successful configurations used 81 load bearing diamonds, or an average thrust/load bearing diamond of less than 5 pounds.

Thrust is a very important factor in determining bit life. Up to the limit of excessive crushing and fracturing the diamonds, it has been found that the higher the thrust, the greater the life, with the differences in life being very significant. The penetration into the rock per revolution of the bit is a linear function of thrust, but there is a threshold thrust below which very little penetration occurs. Therefore, the penetration rate is not proportional to thrust. The actual values for the threshold level and the slope of the curve depend very much on the design and sharpness of the bit, and depend somewhat on the rev/minute. It is significant that, for a partly worn bit, the thrust threshold level in Dresser basalt was approximately 330 pounds which was only slightly below the maximum system thrust of 400 pounds.

The bits, which first exceeded a 100-foot life in Dresser basalt, employed thrusts up to 30 pound/load bearing diamond. These bits showed some diamond fracturing. For the first few feet of hole, the total thrust was held between 700 to 900 pounds to maintain feed rates of between 0.008 and 0.009 inch/revolution. The final bit design employed thrusts between 15 and 23 pound/load bearing diamond (1,000 to 1,580 pounds total thrust) over the life of the bit to avoid excessive fracture.

5.1.2.1.14 Rotational Speed. - The effect of rotational speed on bit life has not been definitely established, but limited testing indicated that lower rpm to a point is beneficial. Temperature measurements of the bits show that a higher speed results in higher temperatures.

There has been evidence to suggest that high bit temperatures lead to greater fracture of the diamonds However, once the fractures occur, the bit becomes sharper and the temperatures temporarily drop. The fact that the bit runs cooler at a lower revolution speed may, therefore, explain why bits last longer; i.e., fewer fractures occur at the cooler tempeatures, and therefore, the overall bit wear rate is slower.

Since a higher rev/minute influences the intensity and type of chatter, a lower speed is beneficial by reducing the effect of this phenomenon. On the other hand, a lower rpm rate results in less footage drilled/hour, and, therefore, requires more man-hours/hole. The final bit design yields an acceptable life in the range of 375 to 500 rpm while drilling at the rate of 2.25 inch/minute in Dresser basalt.

A continuously variable rev/minute control was not available [illegible] radial drill to verify the optimum rev/minute point, which [illegible] the standard radial drill settings of [illegible] to 504 rpm.

5.1.2.1.15 Bit Breakin. - Initially, a bit will cut readily [illegible] thrust. Within one to eight feet of drilling, the initial drill rate falls [illegible] it reaches the rate at which it will drill steadily under a small [illegible] loading for the greater part of the bit's life. It is during [illegible] that the bit may chatter, and the chatter, if present, will be most severe. It has been shown that the initial high cutting rate or the chatter is related to the variance in the protrusion of the diamonds. The higher stones will be absorbing most of the thrust so that individual stones may have extremely high loads. Their cutting rate is therefore high. If their positions or degree of protrusion are such that the cutting action is unbalanced, chatter will occur with resultant diamond fracture. These stones have to be worn down gradually to prevent their overstressing.

The best approach appears to be to run the bit at a lower rotational speed than the nominal value and at a thrust which permits no chatter. This is continued until the drill rate stabilizes, whereupon the normal drilling parameters are applied.

5.1.2.1.16 Chatter. - Without doubt, chatter limits the bit life. Chatter is a complex movement applied to a bit which can be defined as a combination of vertical and horizontal oscillating motions inflicted upon the bit diamonds by a number of causes. The motions' amplitudes will vary unpredictably. Generally, with no other changes being made, the chatter will lessen as the bit wears.

The major effect of chatter appears to be diamond fracture due to the shock compressive loads and/or shear forces imparted. The shear forces can build readily if the diamond skips as a result of a vertical cyclic motion. If the bit matrix or diamond set circle has an inordinate eccentricity, then an oscillatory motion will be imposed on the face stones, and varied stresses will be applied to the ID and OD stones, depending upon their positions with respect to the eccentricity.

If it does not contribute to the catastrophic fracture failure of the diamonds, the minor effect of chatter is to promote horizontal oscillatory translations which increase diamond wear or polishing.

Chatter appears to be affected by:

- Rev/minute - The greater the revolution speed applied to the bit, the greater the amplitude and frequency of the oscillatory motions.
- Thrust - There is a thrust threshold below which chatter occurs. The chatter usually reduces as the thrust is increased.
- Chips - Unsatisfactory chip removal can cause chatter whether the chip removal problem is at the bit face, in the chip release areas, or in the auger flights. These poor chip flow conditions can result from too high a penetration rate overloading the auger, from insufficient clearances between the matrix and rock or between auger and hole ID from too small chip capacity in the auger, chip release areas and chip auger entry, from too many auger flights, from incomplete filling of the auger, from auger whip in the hole due to the hole or auger not being straight, from the differential expansion of the bit crown and blank as the bit warms or cools, from the natural resonance of the core barrel system, and from the variances in the rock properties or structure.

Chatter appears to be somewhat controllable by changing the rev/minute and/or thrust, as long as the bit-rock physical clearances are optimized for the penetration rate and the augers are reasonably well filled.

5.1.2.1.17 Penetration Per Revolution. - The penetration per revolution, or feed, is the advance of the drill into the rock and which therefore influences the "bite" the diamond takes into the rock. The other factor which determines the diamond "bite" is the number of diamonds which cut rock on any given radius measured from the center. For the more successful designs tried, the diamonds were positioned on the face employing two diamonds to a line circle with 0.010 inch spacing between line circles. For a nominal actively cutting width of 0.030 inch, this means that the diamonds from the nearest three line circles cut an arbitrary radius of rock. Thus, at a feed rate of 0.0080 inch/revolution the average bite of the diamond is $\frac{0.0080}{6}$ = 0.0013 inch. Because of variations in diamond shape and protrusion, individual diamonds cut more or less than this amount.

Feed rates much higher than 0.0080 inch/revolution cause early bit failure due to diamond fracture. Feed rates much lower than 0.0060 inch/revolution cause bit failure by diamond polishing. Diamond polishing causes "failure": (1) by requiring more thrust than is available from the drill system, or (2) by causing more heat due to the friction so that the rock burns on the bit face, which blocks the flow of chips.

5.1.2.1.18 Test Material Variations. - Although all of the test rock was taken from the same quarry at carefully selected sites by geologists, the variations in the rock were very noticeable to the eye. The type of rock varies from an almost homogeneous basalt of a dark gray color to a basalt with a variety of light-colored inclusions. Some of these were large white feldspar laths, small particles of olivine giving an overall green cast and areas of martite, an iron mineral, giving a red cast. Figures 5-5 and 5-6 show some of the rock variations encountered.

The effect of the rock variations on the penetration rate was small. It never varied randomly more than 10 to 15 percent during the known thrust operation mode, except at extremely low drilling rates.

The effects on bit life were much more difficult to measure. Since there was no control over the kind of rock encountered as the bit advanced into the test piece, no two identical bits were run for comparison in the different types of rock for their entire lives.

As a result, the variations in bit life from one bit design to the next were certainly affected by the differences in the rock, but to an unknown degree. Hence, interpretation of the test data was complicated by this randomness.

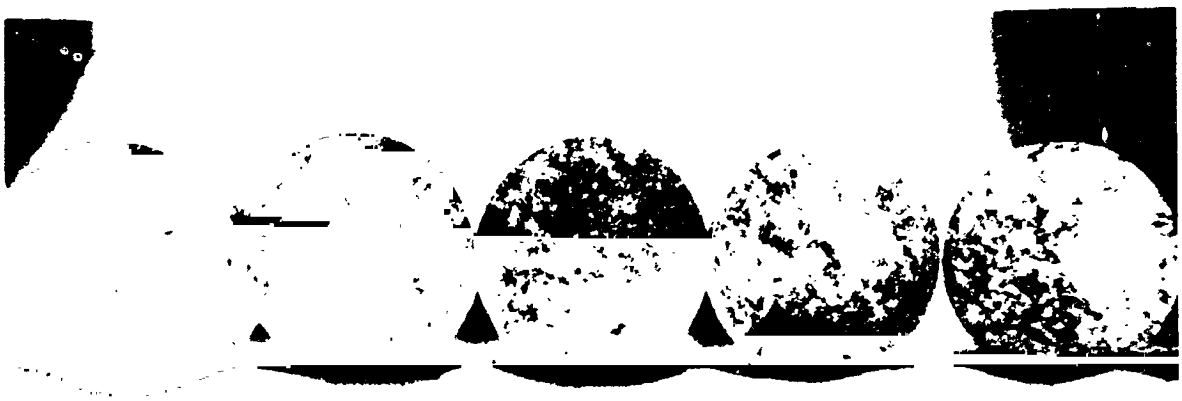

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Figure 5-5. Contract NAS 8-20845 Range of Basalt Macrostructure

Figure 5-6. Contract NAS 8-20845 Massive Inclusion in Basalt

During tests later in the program, it was found that Dresser basalt covered a wide range of hardness (Shore hardnesses 79 to 94), and compressive strengths (40,000 to 74,000 lb/inch^2). These high physical parameters showed up unexpectedly, causing the demise of several bits, and also abruptly ended the life of the bit which had been drilling at a rate of 4.4 inch/minute after accumulating 124 feet of drilling. Other rock anomalies, such as rock fractures and inclusions, apparently limited bit life also. Two bits lost a larger portion of their diamonds when they hit a strata of high silicate and iron content under a fixed feed rate operation mode. The theoretical disadvantage of the fixed feed is that the feed rate may be too high when local hard spots are encountered, and this leads to diamond fracture. Conversely, a fixed thrust mode of operation could lead to impact stresses when the bit breaks through a cavity and then cuts into the bottom of the cavity. The lunar drill engineering model control limits both maximum thrust and maximum feed rate, which should alleviate the problems of over-thrust and over-feed. Unfortunately, the radial drill test setup could operate only either in a fixed feed or known thrust operation mode.

5.1.2.1.19 Bit Life. - It appears reasonable to assume that a dry drilling bit could never last as long as a bit employing air, or water chip flushing methods. From the beginning of the program it was felt that if 100 feet of basalt could not be drilled with one bit using a fluid chip flush, it would appear plausible that the 100-foot bit life goal could not be attained by dry drilling with mechanical chip removal techniques in a lunar environment.

There was an attempt made to use a water chip flush method and two attempts with an air flush method to determine the feasibility of reaching the 100-foot life goal with dry drilling.

Early in the program, using a water flush and drilling at an average rate of 2.3 inch/minute at 700 rpm, a bit cut a total of 32.4 feet before reaching the arbitrary end of life which was set at a drill rate of 1 inch/minute.

This was 3.7 times that of a comparable bit drilling dry using the same drilling parameters. However, the parameters employed were not those found later to be optimum for dry drilling 100 feet of basalt with one bit. On the other hand, the water flush bit was not designed for water flushing, and there were some indications that a redesign of the waterways may have been beneficial. It is unfortunate that an additional bit of the optimized design, operated at the optimized parameters and designed for water flush, could not have been made available for testing. If the 3.7 times improvement over dry drilling could be extrapolated, based upon the maximum dry drilling bit life which is now achievable, then a maximum bit life expectancy in Dresser basalt of approximately 470 feet could be achieved before bit wearout with a water chip flush.

Air flushing appeared to have some advantage over water flushing in creating a bit life standard, since the degree of lubrication and cooling of the diamonds would more closely approximate those of dry drilling. Unfortunately, the two bits tested chattered excessively under the earlier and the optimum drilling parameters. The chatter was found to exist prior to the air test, but became more intense as soon as drilling with the air flush began. Due to the chatter, the bit life was abbreviated. The penetration rates using air flush were greater than without air.

5.1.2.1.20 Bit and Diamond Temperatures. - Among the several bit designs manufactured and tested, bits were made employing diamonds, instrumented with thermocouples, and with thermocouples placed in the crown matrix. Unfortunately, in these bit tests, the diamonds containing the holes for the thermocouples were delivered late in the schedule and the holes had been drilled 90 degrees to the cutting axis. These stones had to be used due to the costs and schedule restraints of the program. The stress imposed by the thermocouplies, which had to be bent through 90 degrees, caused the diamonds to assume a large negative rake. This rake prevented the instrumented diamonds from cutting the basalt, but chip temperatures could be measured at the cutting level.

The maximum chip temperatures measured at the top of the hole were 370°F. The maximum temperature of the chips at the bit face was 680°F near the end of bit life. At a drilling rate of approximately 2.5 inch/minute, the bit face chip temperature was 351°F when the bit was new and operating at 700 rev/minute and 320 pound thrust. The matrix temperatures ran consistently 70°F to 100°F below the diamond temperature.

Later, a modification to the contract permitted correctly instrumented diamonds to be placed into additional bits. The instrumented diamonds actually cut the basalt in these tests. The bit matrix temperatures varied from 290°F to 555°F over the life of the bits. The diamond temperatures showed consistently 30°F to 40°F hotter than the corresponding matrix temperatures. It was found that there was a good correlation between bit temperatures and bit condition, i.e., as the bit wore, its temperature would increase. When the bit matrix reached 500°F, the remaining bit life was found to be very limited.

5.1.2.1.21 Retractable Bit. - A retractable bit concept was developed when there was still doubt that a single bit could drill 100 feet in Dresser basalt. Such a design would obviate the need for removing the entire drill string to replace a bit should a bit wear out or fail before achieving the minimum depth requirements. The bit concept model was manufactured without the diamond crown to demonstrate its principles of operation. The six-bit crown segments are assembled to, or drawn from, the lower end of the core barrel in groups of three. The six segments are attached to a sleeve assembly which permits these group movements. A lip at the bottom of the core barrel limits the extent of crown protrusion. A bit retractor-assembly mechanism, which can be attached to the overshot, latches onto the sleeve and will pull the retractable bit out or insert a new bit and hammer it into place. Figures 5-7 and 5-8 show the insertion-retrieval mechanism and the retractable bit.

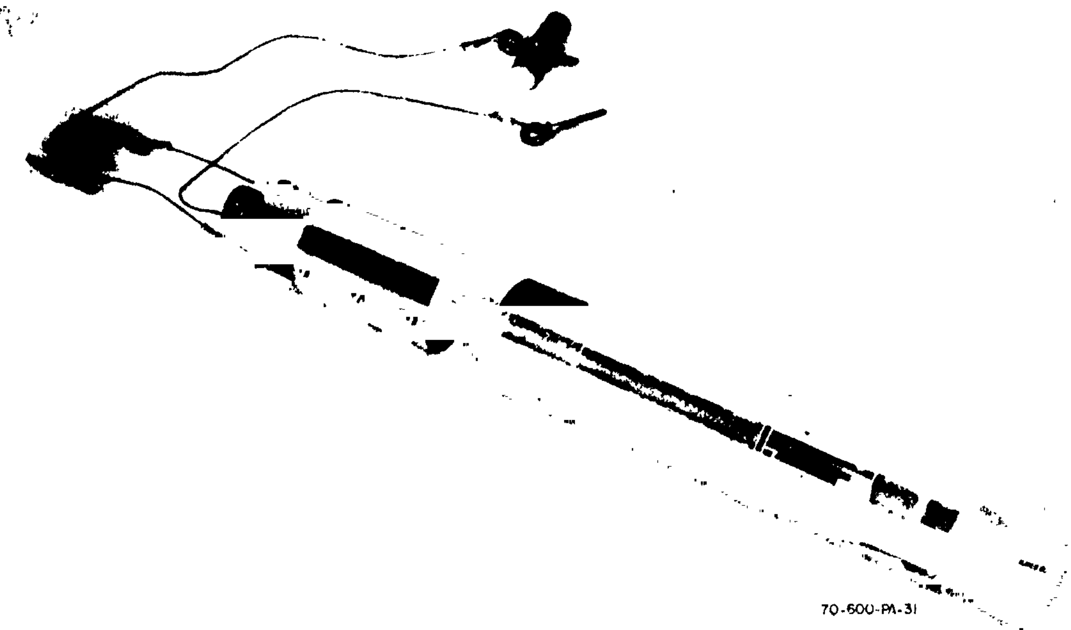

Figure 5-7. Contract NAS 8-20845 Assembly of Retractable Bit and Insertion/Retrieval Mechanism

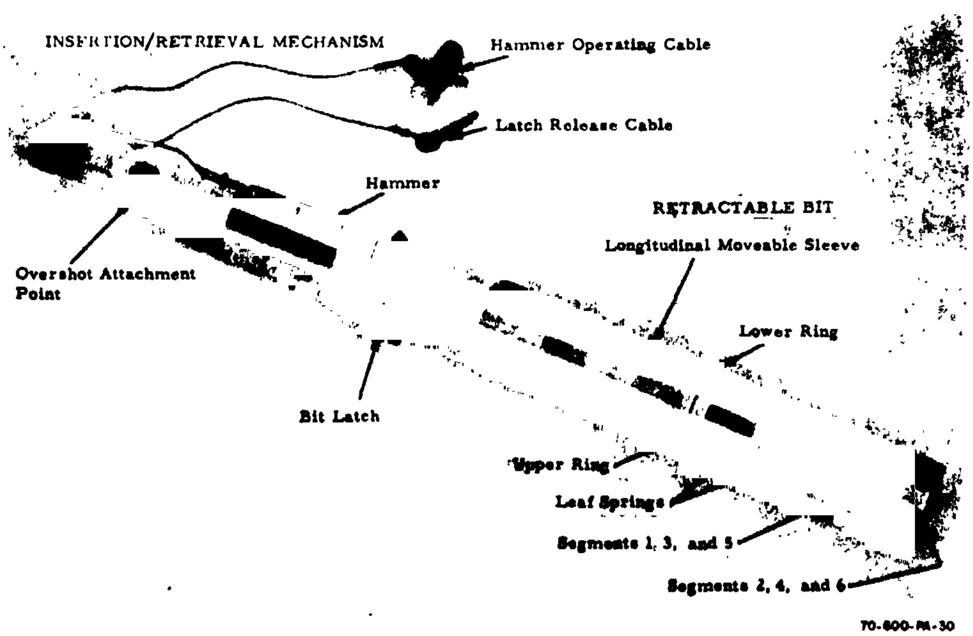

Figure 5-8. Contract NAS 8-20845 Retractable Bit with Insertion/Retrieval Mechanism

5.1.2.2 Bit Manufacturing Study

Although commercial industrial diamond coring bits are considered quality tools, the normal dimensional variables produced by the crystal size and shape of the natural diamonds and the manufacturing process indicated a need for closer control if bits of a quality termed "identical" were to be produced.

5.1.2.2.1 Bit Mold. - A smooth cutting hard carbon was used for a three-piece mold and for the mod inserts employed to form the chip release areas and other crown configurations. The three-piece mold proved necessary to permit the countersinks or pips to be drilled to a specific depth at a given diamond orientation angle within ±5 minutes of arc and to within ±0.001 inch of their specific mold locations. Each of the three pieces which form the OD, ID, and the face of the bit crown was machined to a tolerance of ±0.001 inch. The burr, used to drill the pips, had the maximum included angle of the selected diamond points and took into consideration the angular tolerances experienced in the diamond selection process.

5.1.2.2.2 Diamond Setting. - A skilled diamond setter was employed to set the stones extremely carefully to assure that each diamond presented to appropriate cutting face and that the preselected diamond point was on the bottom of the pip.

The remaining procedures of mold assembly, powder metal loading, compression, blank assembly and sintering were carried through with unusual care to reduce the likelihood of the diamond positions being disturbed.

5.1.2.2.3 Bit Blank. - The bit blank was machined to a maximum run-out of 0.091 inch to avoid the chatter which would be developed by greater eccentricities.

5.1.2.2.4 Mold Reuse. - The mold sections forming the OD and ID of the crown were destroyed in the operations following the sintering process. The portion forming the face generally appeared unharmed but it was not reused.

5.1.2.3 Contract NAS 8-20845 Modification 5

Four bits of the optimized design were manufactured with the ID dimensions which were commensurate with the inner core barrel design. This entailed removing much more metal from the ID than from the ID of the bits which had a life over 100 feet in Dresser basalt. The bits were broken in at MSFC's request at the Hoffman Diamond Products, Inc.. plant in Punxsutawney, Penna. Abnormally high temperatures, which damaged the bits, were reached with the bits; although standard procedures and operating parameters were employed. No definite reason for this phenomenon could be determined. The causative factors could have been harder and higher compressive strength rock, poorer heat conduction due to the new shank dimensions, or poor chip removal.

5.1.2.4 Contract NAS 8-20845 Modification 9

Four bits of the optimized design were tested in a manner to pinpoint the causative factors of the break-in failure of the four deliverable bits supplied under modification 4.

Basalt rock was selected which more nearly met the nominal physical values. The break-in operating parameters were carefully set after a thermal analysis was made which indicated that the wall thickness change should have little effect. The bits were first run at their unmachined ID size and then the shank wall was reduced in several increments to the final size necessary to operate with the inner core barrel. No significant temperature changes were noted. In general, all bits tested well and the tests were concluded early to leave enough remaining life in the bit for preliminary system tests at MSFC.

It was concluded that the major cause of the modification 4 bits was the abnormal rock physical parameters and microstructure.

5.1.2.5 Contract NAS 8-26487

Twelve bits of the optimized design were purchased by MSFC from the Hoffman Diamond Products, Inc. These bits were broken in at MSFC using the lunar drill engineering model and a piece of basalt rock used earlier at the Westinghouse Defense and Electronic Systems Center for the initial systems test. Despite its higher than nominal physical properties, only one bit showed any damage during the tests. Bit 20-52 had some matrix breakage on one segment at the OD periphery, one diamond was lost with the matrix fragment, 8 fractured diamonds on the OD periphery, and some adjacent ID periphery matrix scuffing. A point evaluation by the bit supplier and Westinghouse indicated that the bit design and manufacture was adequate. The damange appeared to be the result of unusual chatter which occurred during the break-in period. The origin of the chatter was not determined.

Bits 20-47 to 20-48 were employed in the systems test at MSFC in the simulated lunar subsurface. Two bits were lost after drilling 27 feet 6 inches and 46 feet 8 inches, respectively, after the drill string began to chatter excessively.

One bit was lost after hitting a quartz strata after drilling 16 feet 5 inches. The fourth bit drilled for 5 feet after which the test was terminated in the interest of preserving the gearbox and other drill components subject to wear for the field test.

5.1.2.6 Future Development Recommendations

Based upon the possibility that the remaining bits might function in a similar fashion to those tested in the simulated lunar subsurface in the nonterminated field test and not reach the goal of a 100-foot bit life, it is recommended that:

a. The field test be carried out to get more data on the average life of the bit.

b. If the average life appears shorter, set up a program to correct the life limiting problems which appear during the field test. At this point in the development, it would appear that the individual segments require some strengthening at the OD periphery.

c. As a backup program, particularly in light of the scientists' desire to go eventually to 1,000-foot depths, the retractable bit design should be developed further, including making actual drilling tests.

5.2 AUGERED CORE BARREL

5.2.1 Contract NAS 8-20547

Since neither a liquid or a gas could be used on the moon to flush out the chips, an auger flighted core barrel was developed under contract NAS 8-20547 to remove the chips from the bit periphery and to lift them to a chip repository. The feasibility of lifting chips out of the hole was demonstrated as one of the priority items during the initial 120 days of the contract.

Extensive auger flight tests at a number of rotational speeds indicated that at the drill speed of 1,000 rpm, a 40-degree pitch was more efficient than more shallow pitches. However, there was some evidence that chip binding increases with the higher pitches; therefore, a compromise auger with a 35-degree pitch was selected.

The drill concept called for the capability of taking 5-foot cores. Density measurements on basalt chips indicated that a given volume of rock produced twice its volume in chips. The volume of the rock removed approximately equaled the core volume. The chip to core volume relationship dictated the design of a 15-foot core barrel and auger flight assembly. Five feet of the inner core barrel portion of the assembly would hold the core, and a 10-foot chip basket would retain the chips.

The core barrel was made up of two sections, an inner and outer core barrel; the outer core barrel drove the bit and removed the chips, the inner core barrel retained the core and the chips so that they could be brought to the surface by the wireline system. The outer core barrel was made up of three mating 5-foot sections (figure 5-9). Five auger flights were ground on the outside of these sections for the purpose of lifting the chips from the drilling area to the top of the 15-foot core barrel. These sections, which were constructed of steel and chromium finished on the outside were designed to give sufficient rigidity to ensure a straight hole and to reduce bit run-out.

Three 1/2-inch-diameter holes were drilled 120 degrees apart at the top of the auger flights in the upper outer core barrel section as entries to the chip basket. No reverse augers or scoops were applied to encourage the chips to enter the chip entry holes. Laboratory chip removal tests, using a plastic tube and simulated chips (Portland cement powder) showed that the auger flight was capable of lifting chips at least 9 feet. A marginal capability of depositing the chips in a chip basket was also demonstrated. A 15-foot chip lifting test was planned, but time and funds did not allow it to be carried out. Chromium plating served to increase wearability and to reduce chip-auger flight friction.

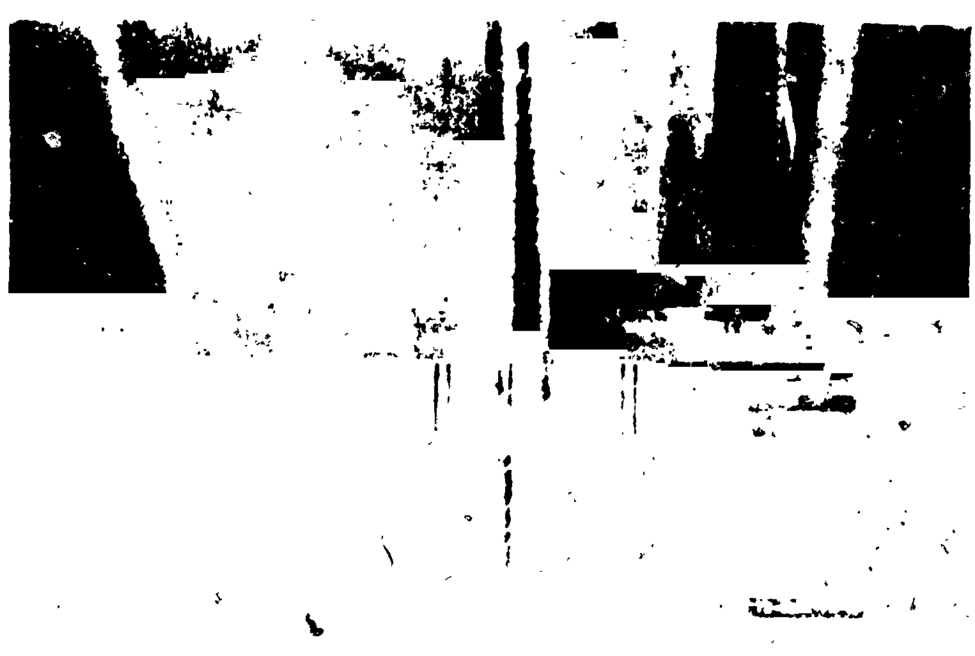

Figure 5-9. Contract NAS 8-20547 Lower Section Augered Core Barrel

Under contract NAS 8-20547, the outer core barrels were made up of two tubes which were pressed together during final assembly; the outer tube carried the auger flights and the inner provides passageways for instrumentation leads, for the coolant water for the steam of the bit thermal control system. The coolant and instrumentation passages mated with corresponding passages in the bit and the drill rods to produce continuity from the bit to the top of the drill string.

The three 5-foot sections of outer core barrel were designed to mate with threaded male and female joints. The threads were cut in a precision manner to ensure that when the threads were tight, and the auger flights were continuous between connecting sections. O-ring and gasket seals were used to prevent leakage. Electrical contact was maintained by pressing the mating connectors together. Alignment of the electrical contacts and the thermal control passages was assured by the precision mechanical thread and the very flat internal shoulders provided.

The outer core barrel fabrication method resulted in serious problems in the final product. All core barrels, which were delivered, were crooked, out of round, and oversize. There was no attempt to utilize these in a systems test.

5.2.2 Contract NAS 8-20845

It was determined under contract NAS 8-20845 that the bit cooling systems and the bit thermal sensing were not necessary. A chip removal study was performed which covered the following physical and operational parameters.

5.2.2.1 Introduction

A theoretical model of the augering system was developed and an augering simulation was set up to test the theory. A major purpose of the testing was to measure the capacity of the augers for various rotational speed and hole sizes. These tests were only partially completed, but enough measurements were made to prove that the auger capacity is far greater than the capacity of the drill bit to generate chips in basalt. The empirical auger rates exceeded the theoretical rates.

5.2.2.2 Test Setup

The test setup consisted of a Longyear 24 drill driving a 3-auger flighted 15-foot simulated core barrel in a 15-foot column of basalt which was partly filled with compacted basalt cuttings. There were three simulated core barrels testing having an auger helix angle of 10, 15, and 25 degrees respectively. The basalt column contained three holes of different diameters which permitted core barrel-hole ID overall clearances up to 0.080 inch. One of the auger barrels was later reduced in diameter to produce an overall maximum clearance of 0.132 inch. High speed and standard rate films were made of the auger action by substituting a transparent plastic tube for the basalt column.

5.2.2.3 Auger Angle

The auger angles tested were 10, 15, and 25 degrees, respectively. The 10-degree auger had the least capacity and required a slightly higher horsepower to remove the chips, due to the drag effect of a larger number of augers/inch. At the lowest test speed (280 rpm), the 10-degree auger chip flow as measured at over twice that of the chip flow produced by the normal bit cutting rates. At the highest speed (1,280 rpm), the flow was measured at a rate of 22 inch/minute. The theoretical value was based upon equal friction between the hole and the auger, and it was assumed that the chips in the space between the hole and the auger were not transported upward. The observed high flow rates can be explained theoretically if the chips are considered cohesive enough so that, within a given rpm range, they rise in a slug flow mode. The friction between the auger and chips must be very slight so that few or no chips are rotating with the auger.

5.2.2.4 Auger Depth

Theoretically, the initial auger designs will carry the expected volume of chips generated at any revolution speed tested. Under a high penetration rate and chatter conditions, there were occasions when auger depths of 0.030 inch appeared marginal in capacity. In general, 0.050 inch deep augers appeared to be satisfactory if the other chip flow controlling factors were optimized.

5.2.2.5 Auger Power Consumption

Power consumed was increased as the clearance between the auger and the hole ID decreased. When the 15-foot auger was used in each of two test holes, an additional 1/2 hp was required to auger chips at the same revolution speed in the hole which was 0.050 inch less in diameter. Until the speed reached the maximum (1,280 rev/minute), the effect of length of the auger flight appeared to have less effect on the horsepower requirements than expected. For example, a 5-foot, 2.010 inch OD, 15 degree auger, running in a 2.080 inch hole at 640 rev/minute, required 2 hp. Under the same conditions, a 15 foot length required approximately 2.7 hp.

5.2.2.6 Auger Chatter

The auger will chatter in the hole due to the so-called dry shaft whirl effect. This is caused by a combined effect of friction and centrifugal force in the absence of a lubricant. As the shaft whirls against the sides of the hole, the buildup of friction can be so high that the shaft can be stopped. The chatter problem was more severe for the 10- and 15-foot auger lengths and the higher revolution speeds. Chips coming up the augers act as a lubricant - reducing or eliminating chatter. However, if the rotational speed gets high enough to clear, to a large degree the augers at normal feed rates, then this chatter phenomenon occurs more readily. If the clearance between the auger OD and the hole ID is of the order of 0.020 inch or better, the chips seem to prevent the chatter at any rpm used. It is possible that, if the auger had been stabilized by a bit on the lower end during the tests, the tendency to chatter would be further reduced.

5.2.2.7 Optimized Design

The 15-degree auger was selected since it had a good safety factor capacity, remained reasonably full at the normal range of rpm keeping chatter at a minimum, and required less horsepower than the 10-degree auger. A 0.040-inch auger hole clearance was selected, as well as a 0.050-inch auger depth. A complete set of 3- to 5-foot sections of augered core barrel sections was delivered for use in the laboratory and field tests.

5.2.2.8 Contract NAS 8-26547

The augered core barrel worked well individually and collectively in the lunar drill system tests at MSFC.

5.2.2.9 Future Development Recommendations

Unless future field tests show otherwise, no further outer core barrel developments appear to be indicated.

5.3 AUGER CHIP ENTRY

If the chips are moved satisfactorily from the bit face to the auger flight entry, and then up the augered barrel, they then must be moved efficiently to the interior of the augered core barrel and be deposited into a chip storage container (chip basket).

5.3.1 Contract NAS 8-20547

Under contract NAS 8-20547, the upper end of the upper auger barrel section delivered contained three 1/2-inch diameter holes spaced 120 degrees apart for chip entry. No attempt was made to utilize reverse augers or scooping devices to force the chips inwardly. This type of entry proved to be marginal.

5.3.2 Contract NAS 8-20845

Under contract NAS 8-20845, a computer designed set of auger entries was placed at the top of each of the three auger flights (figure 5-10). These entries were aligned with the auger flights so as to scoop up the advancing chips and rechannel them inward. To prevent the possible bypass of the chutes by the chips, reversed augers were located just above the chutes to pump back down any chips which passed the entries.

The pressure produced by the slug-type chip flow and the reverse auger action appeared to push the chips into the chip basket satisfactorily in the auger tests.

5.3.3 Contract NAS 8-26487

The laboratory tests showed that when working with the Lunar Drill System, the chip entry worked well.

Figure 5-10. Contract NAS 8-26487 Auger Chip Entry

5.3.4 Future Development Recommendations

Unless the future field tests show otherwise, no further auger entry development is indicated.

5.4 DRILL ROD

5.4.1 Contract NAS 8-20547

Under this contract, the drill rods were made in 5-foot lengths of extruded aluminum. Each rod had four coolant passages (1 liquid, 3 steam) and four channels for instrumentation. The coolant passages mated positively through male and female fittings. The rod sections were joined by an external coupling which utilized guides and a segmented thread coupling similar to a breechblock locking mechanism (figure 5-11). The contacts and coolant passages were first mated and then the coupling was given a quarter turn to firmly connect the rod. The integrity of the coolant passages relied upon O-ring seals, and the electrical contacts relied upon mechanical pressure (figure 5-12).

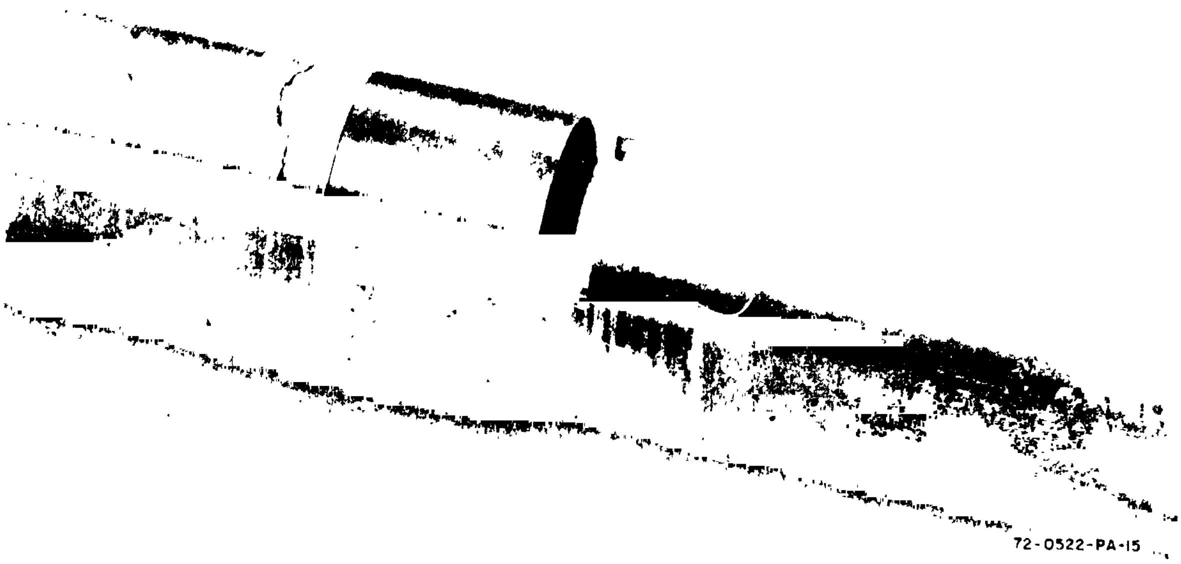

Figure 5-11. Contract NAS 8-20547 Drill Rod Coupling

Figure 5-12. Contract NAS 8-20547 Showing Coolant Passages and Electrical Contacts

The rods were statically pressure tested, but no operational tests were required as part of the contract. The reliability of the rods in long strings was expected to be low in these engineering models, and the coolant passage seal insertions required more dexterity than an astronaut possessed.

5.4.2 Contract NAS 8-20845

The redesign of the drill was made under this contract reflecting the deletion of the bit cooling system and the bit thermal sensing circuitry. The design (drawing WE 2201) was manufactured by MSFC using steel tubing instead of aluminum. These rods screwed together into the same thread design used for the core barrel and chuck (figure 5-13).

5.4.3 Contract NAS 8-26487

The rods performed well during the laboratory tests at MSFC.

5.4.4 Future Development Recommendations

Unless future field tests show otherwise, no further drill rod development is indicated.

5.5 INNER CORE BARREL ASSEMBLY - CHIP BASKET

5.5.1 Contract NAS 8-20547

The inner core barrel and chip basket assembly was designed to lock into place inside the lower outer core barrel section and was used to retain and recover the core and the chips. The inner core barrel assembly is then divided into three parts - a core barrel 5 feet long and two 5-foot lengths of chip basket. Openings in the upper outer core barrel section allow the chips that have been augered to the top of the core barrel to enter the chip basket (figure 5-14).

The inner core barrel fastened to the outer core barrel by means of a locking assembly but could remain stationary with respect to the outer core barrel by rotating around a bearing in the locking assembly. The upper two sections (the chip basket sections) were attached directly to the locking assembly and, hence, rotated with the outer core barrel.

Figure 5-13. Contract NAS 8-26487 Drill Rod In Place

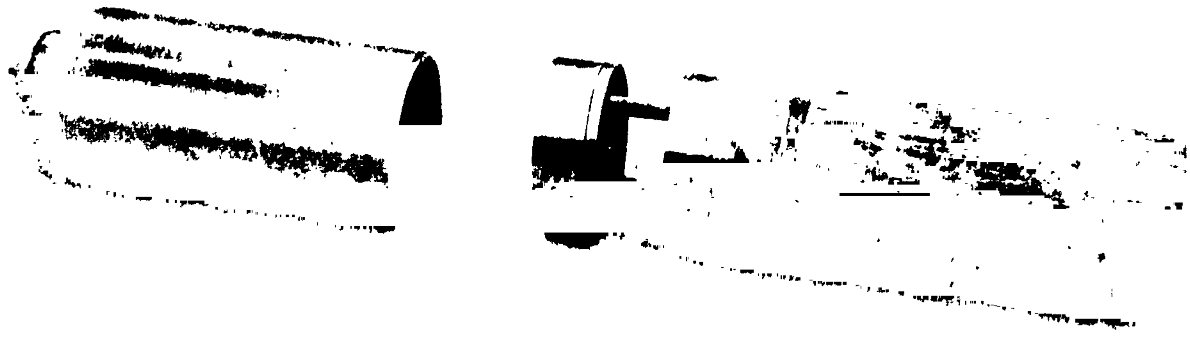

Figure 5-14. Contract NAS 8-20547 Chip Basket Entry and Overshot Attachment Point

The two sections of the chip basket are screwed together (figure 5-15). The upper section contains a valve which remains open during drilling but is shut manually when the inner core barrel is being disassembled after being retrieved. The closed valve prevents the chips in the upper basket from dropping out, as the two sections are being separated, preventing a loss of the chips.

The lower end of the inner core barrel is provided with a mechanism which grasps the core as it is pulled upward. When the reduced cutting rate of the drill activates the "pull core" signal, the drill is stopped automatically. As the entire drill string is raised slightly, the core lifter, in the inner core barrel, grasps the core and breaks it free approximately at the core-rock interface.

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Figure 5-15. Chip Basket Connection and Upper Section Valve

As discussed previously, the entire drill string need not be removed to recover a core. Initially, the inner core barrel retrieval was accomplished by dropping a "wireline" with the attached magnetic overshot down the drill string. The magnetic overshot engaged the top of the inner core barrel locking mechanism for the first three drill strokes. As an upward force is exerted, the inner core barrel assembly is unlocked and drawn up to the surface. The chip basket assembly is added at the same time as the first drill rod (15-foot depth point). The overshot then locks the top of the upper chip basket.

5.5.2 Contract NAS 8-20845

Under contract NAS 8-20845, the concept was changed. In the original concept, the chip basket was permitted to rotate with the outer core barrel. In such a configuration, those chips entering the chip basket would shortly thereafter be thrown to the sides of the basket under the influence of the strong centrifugal force. Potentially, these chips could accumulate to the extent that they could bridge and choke off the basket area beneath the blockage. To prevent this condition, the entire chip basket and inner core barrel assembly was separated from the locking assembly to the outer core barrel by means of a bearing. This design keeps the entire inner barrel assembly stationary with respect to the outer barrel when the core is entering the inner core barrel.

To ensure that the chip streams entering the chip basket do not meet and form a bridge which would prevent further chip entry, a vaned entry (figure 5-16) was set at the top of the upper chip basket. As the outer barrel chip entries revolve about the vaned section of the upper chip basket, the vanes chop the incoming chip streams so that the bridging potential is limited.

The locking device to the outer barrel is positioned on top of the chip basket vaned section. The lower portion of the inner core barrel assembly is prevented from moving off the drill rotational axis by a stabilizing ring fastened to the ID of the lower outer core barrel section and by the contour of the core lifter case matching the contour of the ID of the bit. Small clearances are provided to assure ease of rotation.

A spear-like device is fastened to the top of the locking device at the top of the inner core barrel assembly for the mechanical overshot to clamp on.

5.5.3 Contract NAS 8-26487

During the laboratory system test at MSFC, the chip basket sections, valve, and locking device performed as intended.

5.5.4 Future Development Recommendations

Unless the field tests show otherwise, no further chip basket development is indicated.

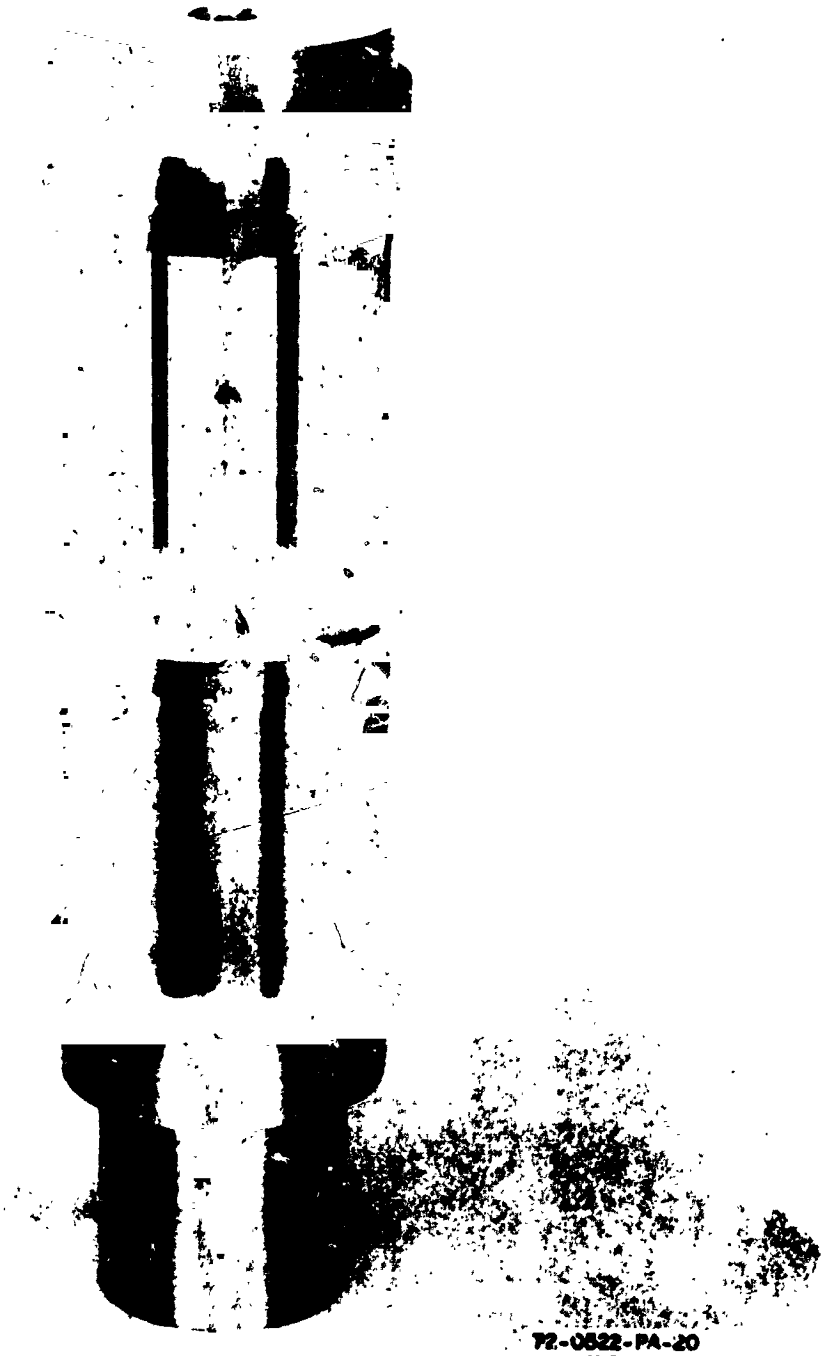

Figure 5-16. Contract NAS 8-20845 Vaned Entry to Chip Basket

5.6 INNER CORE BARREL ASSEMBLY - CORE BARREL

The inner core barrel is designed to accept the core and to provide a method of grasping the core during the core breaking procedure.

5.6.1 Contract NAS 8-20547

Under contract NAS 8-20547, the 5-foot-long inner core barrel was fastened to the outer core barrel by a locking device which could rotate with respect to the outer core barrel by means of a bearing set in the locking device. The chip basket was fastened to the upper portion of the locking device and rotated with the outer barrel.

The locking device could be unlocked by an upward pull by the overshot either on the core barrel locking device within the first 15 feet of hole or on the chip basket top at greater depths (figures 5-17 and 5-14).

The core lifter assembly was located at the downhole end of the inner core barrel. The core lifter is an assembly which permits the core to pass through as the hole is drilled. When the 5-foot stroke is completed, the

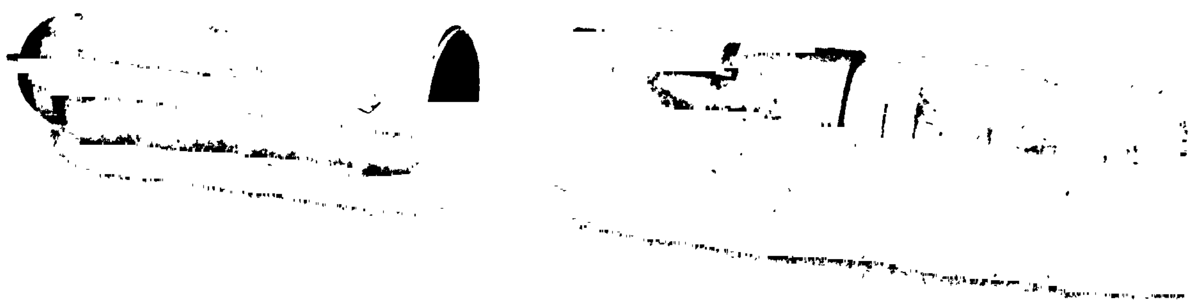

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Figure 5-17. Contract NAS 8-20547 Inner Core Barrel Locking Device and Overshot

drill is stopped and the entire drill string is raised slightly. The core lifter is a ring wedge which is forced by the upward movement between the core lifter case and the core and exerts a squeeze on the core. Raising the drill string further exerts enough tension on the core to snap it. The inner core barrel assembly is then pulled to the surface by the wireline.

The core lifter and core lifter case were modifications of existing designs (figures 5-18 and 5-19). Some difficulty was experienced during the core breaking operations with the core not breaking cleanly above the crown ID. On several occasions, the rock broke downhole of the crown with the section of rock immediately below the crown being larger than the ID of the bit. This situation prevented the inner barrel removal and required that the drill string be removed and the extra rock be broken off before the core could be removed. A redesign of the bit/core lifter case/core lifter interface appeared necessary to correct this condition.

No system test was made using the entire inner barrel assembly.

5.6.2 Contract NAS 8-20845

Under this contract the inner core barrel was fastened directly to the chip basket. The entire 15-foot inner core barrel assembly rotated around the bearing in the locking assembly which was located above the chip entries. The inner core barrel was capped on its up-hole end by a male threaded solid cylinder.

Initially, a special core lifter design was provided which attempted to prevent the inner core barrel from rotating. It employed a diamond to score a groove into the core as the core passed up into the inner core barrel. A tungsten carbide key insert in the ID of the core lifter case was supposed to follow in the groove preventing inner core barrel rotation if the core remained solid. Since the core does not always remain intact and since the core lifter exhibited tendencies to override the tungsten carbide insert and prevent core entry, a more conventional type core lifter and core lifter case assembly was produced. Although there was some concern over the

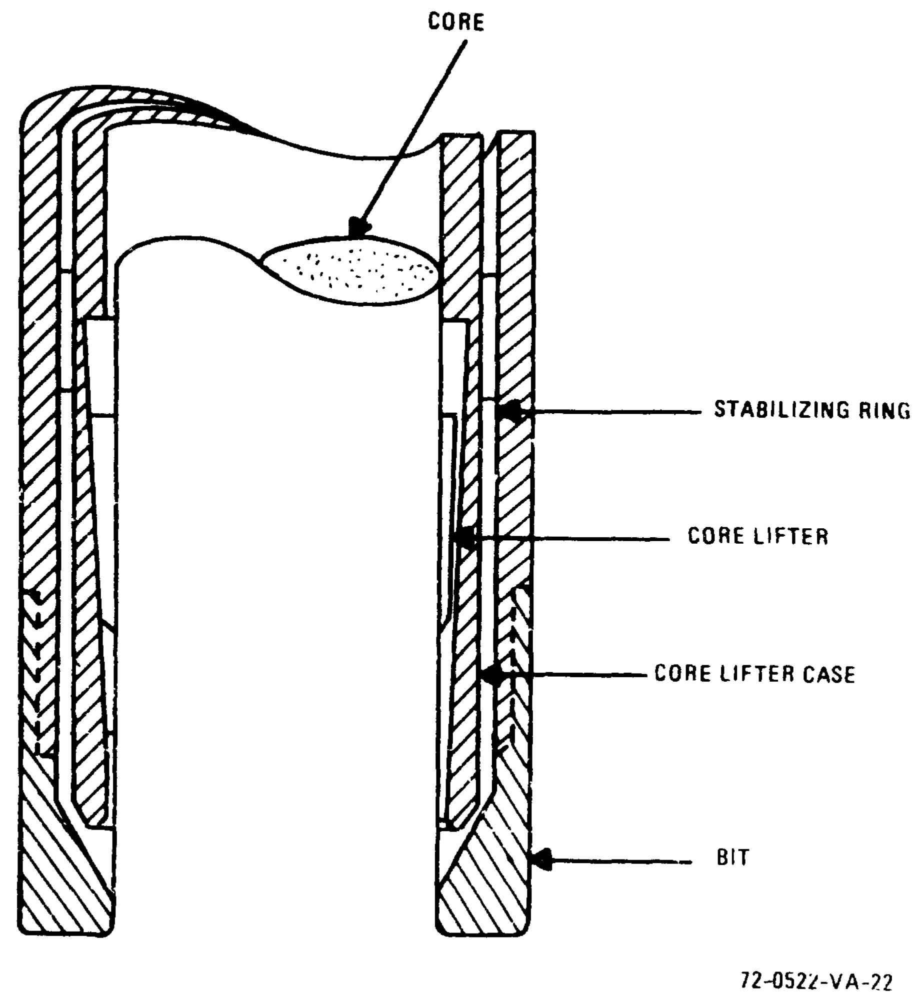

Figure 5-18. Contract NAS 8-20547 Cross Section of Lower Portion of Inner Core Barrel

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Figure 5-19. Contract NAS 8-20547 Core in Core Lifter Case and Typical Piece of Core

possibility that the inner core barrel bearing friction would produce a torque reactance greater than the force exerted by the core lifter assembly on the core or core fragments, the new design worked well during the MSFC laboratory tests. The core lifter case showed no excessive abrasion, indicating that it stabilized the inner core barrel without slippage during the preliminary system testing. The core lifter required a heat treatment before it consistently grabbed the core.

The core breakage was clean and above the crown as intended.

5.6.3 Contract NAS 8-26487

In general, the inner core barrel worked well recovering approximately 100 percent of the core (figure 5-20). There was some difficulty with core blockage, when dacite was drilled, due to its sticky chips adhering to the core or getting in between the core lifter and core. The core lifter was shortened to increase the core-core lifter clearance but only a modest improvement resulted (figure 5-21). Additional clearances were recommended.

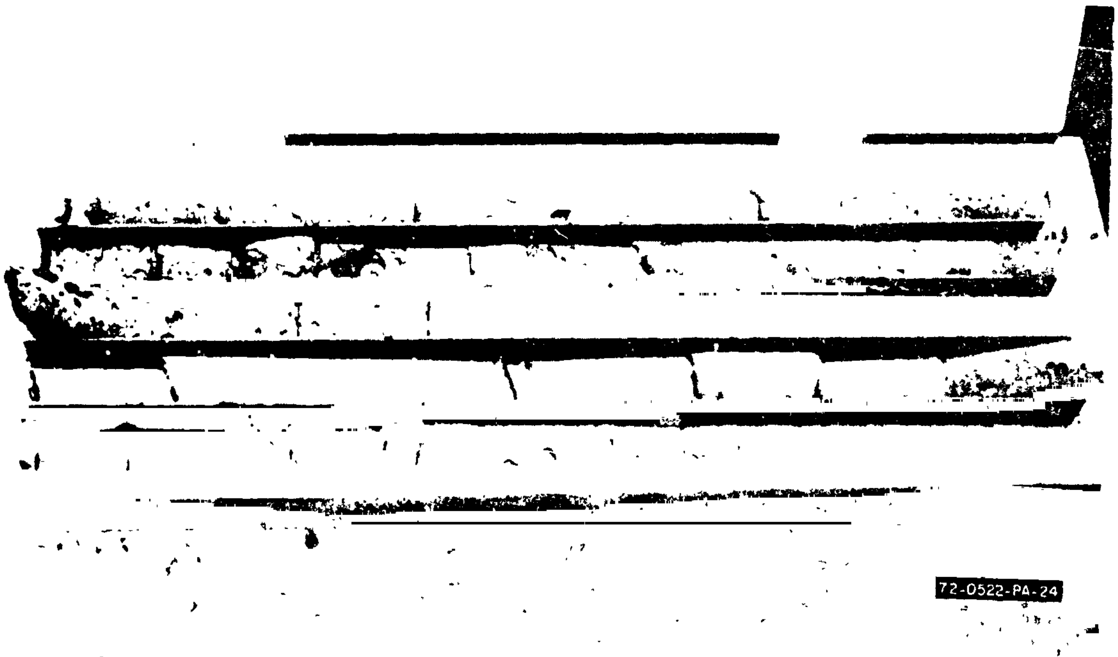

Figure 5-20. Contract NAS 8-26487 Typical Core Cut During Systems Tests

Figure 5-21. Contract NAS 8-26487 Dacite Core Jam In Core Lifter Case

5.6.4 Future Development Recommended

It is recommended that further studies be made to determine the optimum core lifter design which will reduce chip/core jamming.

5.7 CHUCK AND ROTARY JOINT

5.7.1 Contract NAS 8-20547

The chuck provided the interface between the drill rods, the gearbox, and the rotary joint. Coolant and electrical signals were passed through the rotary joint into the chuck. The chuck transmitted torque to the drill string by mating with the gearbox bull gear through a splined connection and connected to the drill rods with the same coupling that connected the drill rods. An adapter was provided to allow the chuck to be used with the core barrels for the first 10 feet of drilling.

The chuck (figure 5-22) was lowered or raised to make minor vertical adjustments to match the height of the drill string section in the drill by means of a thread-knurled nut arrangement which rested upon the top of the bull gear hub. The drill string piece (rod or core barrel adapter) fastened

Figure 5-22. Chuck

to the segmented thread lower end of the chuck. The thrust reactance was through a "C" ring which fit into a groove in a groove just below the bottom of the bull gear hub.

The rotary joint was connected to the top of the chuck with its coolant and steam passages connecting on the inside of the chuck. The electrical connections were made along the vertical axes of the rotary joint and the chuck. The rotary joint had to be removed from the chuck each time the inner core barrel was retrieved.

The rotary joint was necessary to provide coolant to the rotating drill string and bit as well as to provide a continuation of the signal path from the drill bit to the monitoring equipment. The rotary joint is attached to the top of the chuck and connected to the bit radiator and control panel on one end and the drill string coolant channels and bit instrumentation on the other. A modification of a standard rotary seal was used for the water and steam transmission, and a rotary transformer was incorporated internally for the transmission of the instrumentation signals. Figure 5-23 shows the rotary joint.

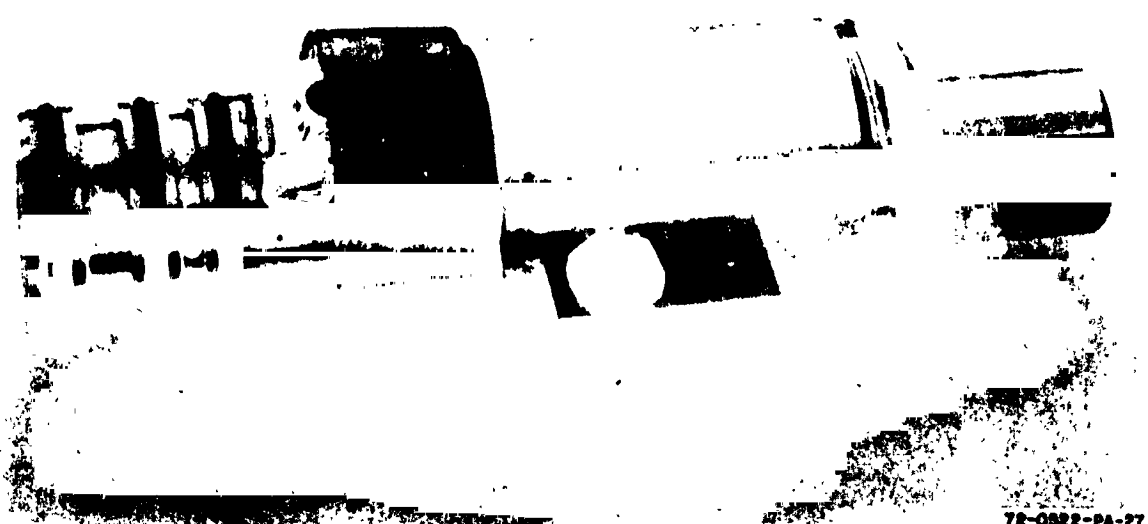

Figure 5-23. Rotary Joint

Since the rotary joint was vital to the operation of the lunar drill concept, a feasibility demonstration of the rotary joint during the first 120 days of the contract was a contractual requirement. No leakage or ice formation was observed and visual examination of the dynamic seal showed no deterioration due to ice.

Development tests showed that the rotary seal was adequate; although, the mechanical design of the housing and manufacturing techniques needed improvement.

5.7.2 Contract NAS 8-20845

Under this contract, the chuck was redesigned and the rotary joint was eliminated since the bit cooling system and bit temperature sensing was abandoned.

The chuck design was a simplification of the previous design which had the same arrangement for making a vertical adjustment for thrust reactance but had a male thread on the bottom which matched the female threaded end on each of the other drill string elements. Cooling passages and wiring and electrical contacts were eliminated. The inner core barrel sections and the overshot could be put through the chuck whenever necessary.

5.7.3 Contract NAS 8-26487

The chuck performed as expected during the MSFC laboratory tests.

5.7.4 Future Development Recommendations

Unless future field tests indicate other difficulties, the sole development recommendation is to redesign the shoulder at the end of the thread on the lower end of the chuck. The current design causes a permanent expansion of the end of the drill string section attached to it.

5.8 DRIVE MECHANISM

5.8.1 Drive Mechanism Design

The drive mechanism must perform three primary functions:

- Transmit torque from the motor to the drill string
- Advance and retract the drill string
- Provide power to operate the hoist to raise and lower the inner core barrel.

5.8.2 Contract NAS 8-20547

These three functions were performed through the integrated gearbox and hysteresis clutch mechanisms under this contract.

The gearbox assembly provided a neutral position and two forward drill string rotational speeds of 200 and 1,000 rpm from the nominal 6,000-rpm input from the motor. The 1,000-rpm rate was used for normal drilling, and the 200-rpm rate was provided for emergency high torque operation. The gear box was designed to deliver 60 foot-pounds under normal operation and 300 foot-pounds at the 200-rpm speed.

The gear case was made of aluminum to conserve weight. The gears were made of a vacuum melt steel with a carburized case depth of 0.025 to 0.035 inch. Originally, the gear train was lubricated by transfer from solid lubricant idler gears and the bearings were lubricated by solid lubricant ball retainers. Figure 5-24 depicts the gearbox assembly with the air-cooled motor mounted to it.

The hysteresis clutch was used to drive a 160-to-1 harmonic drive which moved the drill string in the vertical direction, raised or lowered the inner core barrel assembly through the hoist mechanism, and provided the core breaking force to the drill string. It was located in the metal can on top of the gearbox case immediately behind the lefthand ball screw (figure 5-24). A manual gear shift lever was provided to apply the output of the harmonic drive to the hoist or the ball screws. Sufficient speed control was provided to permit advance or retract rates from 1/4 to 4 inches/minute and hoisting and lowering rates of the inner core barrel from 0 to 7-1/6 inches/minute.

The steel ball screws were designed to allow a large mechanical advantage between the hysteresis clutch and the drive mechanism. The ball screw assembly was basically a conventional design, but the screws were hollow to conserve weight. The bearing surfaces were lubricated by a molybdenum disulfide coating and were kept clean by special nylon wipers. A downward force of 400 pounds for drilling and an upward force of 2,000 pounds for breaking could be applied.

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Figure 5-24. Conventional Commercial Motor Mounted on the Gearbox

The analysis of the requirements for the gearbox and other mechanical parts to operate in a vacuum, the weight restraint, the possible gearbox oil sealing difficulties, the high motor input speeds, and the possibility of high gear and bearing temperatures indicated that the best probability of operational success lay in the use of solid lubricants.

The Westinghouse Research Center, Churchill, Pennsylvania, was given a subcontract to modify standard high quality bearings to accept solid lubricant ball retainers and to provide solid lubricant gear blanks to be made into idler gears which would lubricate the gearing through a transfer mechanism.

The experience with solid lubricant bearings had been extensive in laboratory applications. Experience had shown that bearing lives in excess of 300 hours, at 10,500 rpm and under loads similar to those expected in the gearbox, could be achieved. Vacuum operation appeared to have little effect on bearing life. However, extrapolating laboratory experience to a gearbox environment was considered to have some risk.

The experience with solid lubricant idler gears was not as extensive, and this experience was attained with relatively slower operational speeds, different gear designs, and loads.

A development testing program was recommended by the supplier, but due to funding and schedule restraints, it was decided to proceed with the bearing and gear lubricating designs based upon the available experience.

Since the method by which solid lubricants function is that of sacrificial wear, there is a chance always of a buildup of wear debris. The solid lubricant design was only partly successful.

Interface difficulties and manufacturing tolerance buildups resulted in low preloading of the bearings.

Several bearings were damaged due to improper handling during installation and disassembly operations and as secondary failures resulting from contamination by metal chips from external sources.

The solid lubricant idler gears which operated at the higher gearbox speeds failed repeatedly while those operating at or below 1,000 rpm operated as designed. The failures of the high speed idler may be attributed partly to the material, the loading, their type of mounting and the generous clearance of the gearing at normal ambients. The clearances were the results of allowing for the linear expansion of the gears over the design range of -40 to 165°F and the compensation for the differences in the coefficient of linear expansion between the steel gears and the aluminum gearbox over that range.

The high speed idlers were eliminated from the assembled drill system. The high-speed gears in the assembly system were lubricated periodically with Apiezon H grease containing zinc oxide and molybdenum disulfide in proportions by volume of 8-3-1 respectively.

Westinghouse Central Research Laboratories evolved a design of a new idler gear and mount consisting of a porous ployamide gear which permits a low vapor pressure oil to be bled from a central oil reservoir. This design was not manufactured due to funding and schedule restraints.

Approximately 35 hours of operation were accumulated on the box prior to shipment to MSFC. During this time, the major failures were idler gear and bearing failures. In general, the solid lubricant bearings operated satisfactorily despite low preload. The conventional gearing had no failures, although one jack shaft containing an integral gear was replaced due to slightly undersize splines causing wobble in a gear containing the mating splines. The hysteresis clutch has exhibited no failures of its solid lubricated bearings and gears.

5.8.3 Contract NAS 8-20845

Under this contract a portion of the gearing was redesigned to reduce the maximum output rotary speed to 504 rpm. Since the reduction in speed would have reduced the low speed from 200 rpm to approximately 100 rpm and raised the torque to 600 foot-pounds, there was a concern about the available torque being greater than the drill string could withstand. Consequently, the lower speed was eliminated and only two gear shift positions were made available - neutral and high speed.

Since the lunar drill model was to be used beyond the 160 hours expected life in the laboratory and field tests, the gearbox solid lubricated bearings were removed and replaced with standard bearings. A pressurized oil lubrication system was installed and an external pump was provided to pump the oil through the gearbox.

5.8 4 Contract NAS 8-26487

Since the maximum vertical speed was limited to a maximum of 4 inches/minute downward and approximately 4 inches/minute upward and since the major transfer gear in the hysteresis clutch was made of solid lubricant with a limited expected life, a small reversible motor was utilized to replace the hysteresis clutch. A slight change was made in the circuitry design so that the preset thrust load could be applied and/or the feed rates kept constant with the existing semiautomatic control unit.

The drive motor speed was adjusted electrically so that the drill string rotary speed approached 400 rpm. The gearbox functioned as intended during the system tests at MSFC; although, the hoist was not used to raise or lower the inner barrel components through the wireline. This was done manually through a separate pulley and line arrangement.

5.8.5 Future Development Recommended

As designed, the gearbox may function well during the future field tests. However, the following development efforts are recommended:

a. Refine the lubrication system with the goal of eliminating the oil pressure pump.

b. Make a new study covering the application of solid lubricants since great advances have been made in this field since the original gearbox design.

c. Study methods of eliminating the complexity of gearing by considering other methods of speed reduction and power drive.

5.9 DRIVE MOTOR

5.9.1 Contract NAS 8-20547

The motor design, selected for this contract, was a 100-volt dc motor capable of delivering 60 inch-pounds at the normal operating shaft speed of 6,000 rpm. The motor was sealed for vacuum operation. The motor was pressurized to 50 psi with nitrogen and fluid-cooled with U-CON (polyalkaline glycol) oil. Pressurization was necessary to reduce cavitation conditions at the coolant pump.

Heat was removed from the motor armature in two ways. The pressurized gas carried some heat to the motor case by convection. The coolant flowed through coolant tubes, which were wound around the case to remove this heat and the stator heat and to carry it to the radiator. The majority of the heat was removed by the circulation of the coolant fluid through the motor itself. The coolant entered the top of the motor and was pumped through the hollow rotor shaft to a sump at the base of the motor case. The pump, located in the bottom of the sump, was a simple impeller designed to force the coolant out of the sump, through the radiator and back to the motor. Figure 5-25 is an end view of the assembled motor.

A limited amount of operational data was gathered on the motor. However, during this test period, a number of problem areas arose. As a result of the compromises which were made in the design in order to reduce weight and size, the commutator length and brush area were smaller than would normally be expected for a motor of this power rating. The smaller size, combined with the apparent deleterious effect of the U-CON, resulted in unusual mechanical wear of the commutator. It was estimated that the maximum operational life of the motor would be 8 to 10 hours before refurbishing of the commutator was required. In addition to contributing to the commutator and brush problem, there was evidence that the U-CON may have attacked other materials internal to the motor.

Figure 5-25. Sealed Drill Motor

The impeller, which was to be used to force the oil through the system, was unsatisfactory. Gas bubbles occurring in the coolant system bound the impeller which reduced the total amount of coolant circulated. While it was felt that the design of the impeller was the problem, repeated attempts to improve the design were unsuccessful. In the delivered motors, the impellers were removed and an external coolant pump was provided to ensure the proper flow of U-CON through the motor.

Because of the low reliability of this motor design, a conventional commercial motor was furnished for laboratory and field system test purposes. Figure 5-26 shows this motor mounted to the gearbox.

5.9.2 Contract NAS 8-20845

During this contract there was no development of the drive motor. The conventional motor was utilized to make demonstration augering and drilling tests in limestone.

Figure 5-26. Air-Cooled Motor Mounted on Gearbox

5.9.3 Contract NAS 8-26487

The conventional motor was employed during the drill system test at MSFC and worked well. The speed had been reduced to approximately 400 rpm by reducing the voltage on the armature.

5.9.4 Future Developments Recommended

Although the commercial motor functioned as intended, for lunar application the following developments are recommended:

a. Study the concept of a liquid cooled motor to eliminate the problems occurring with the present design.

b. Study the concept of a gas cooled motor.

c. Study the concept of a different type of motor capable of providing a range of rotational speeds and torques which might use the cooling approaches of either a or b and which might be useful in reducing the complexity of the gearbox.

5.10 OVERSHOT

5.10.1 Contract NAS 8-20547

The E.J. Longyear wireline concept provides for an overshot which locks over a spearhead whose base is attached through a latching device to the inner core barrel assembly. The force which springs the overshot clamp over the spearhead is supplied by the kinetic energy of lowering the overshot and the weight of the overshot. After the inner core barrel assembly is emptied, it is returned to its operating position. A special sleeve is used on the overshot for this operation which forces the clamp open when the weight of the inner core barrel on the clamp is relieved by its reaching its operating position. The overshot then can be withdrawn.

In keeping with the concept that the reduced gravity on the moon would require a larger mass to perform the same clamping action, an overshot employing magnets was designed to keep weight to a minimum (figure 5-27). The principle of operation was to use the maximum force exerted by the

Figure 5-27. Contract NAS 8-20547 Magnetic Overshot

magnets to lift the full inner core barrel assembly. A lesser force was created by introducing an air gap, between the overshot and inner core barrel assembly to which it attaches, to lower the inner barrel or inner barrel assembly into its locking position inside the outer core barrel.

The force necessary to release the lock was greater than the magnet holding force and an upward pull would release the overshot.

The overshot was designed to have a maximum 85-pound pull for raising the full inner core barrel assembly and a 20-pound pull for lowering the empty core barrel and releasing the overshot. The dimensional restraints imposed by the drill string ID and the degree of effectiveness of the available magnets resulted in a maximum 60-pound and a minimum 14-pound pull. Although a 60-pound pull is entirely adequate to lift the 28-pound weight of a loaded inner core barrel, it was not sufficient to pull the core barrel free from the slight wedging of the inner core barrel which occurred during core break.

5.10.2 Contract NAS 8-26487

It was required that a new overshot design be made which could be used with the lunar drill during the MSFC laboratory system test and in the field. The most inexpensive and readily available one was a Longyear Type AQ Wireline Overshot (figure 5-28). This unit had to be modified by adding sleeves in three locations so that it would fit snugly into the drill string and would keep the overshot spearhead latch centered. A Longyear AQ spearhead was added to the upper end of the inner core barrel assembly locking mechanism. The overshot system worked as intended although the spearhead latches needed adjustment periodically. The length of the overshot assembly requires a redesign of the hoist frame which was not a part of this contract. During the MSFC laboratory tests, the overshot was raised and lowered manually with the wireline cable going over a pulley mounted in the laboratory superstructure above the lunar drill test site.

5.10.3 Future Development Recommendations

Although the overshot functioned well during the tests at MSFC, it may prove to be too large for lunar use. The following development studies are recommended:

a. Study the existing Longyear design to determine whether it can be reduced in size and weight.

b. Study other schemes of latching and unlatching which would require less astronaut participation.

Figure 5-28. Contract NAS 8-26487 Mechanical Overshot

5.11 DRILL FRAME

5.11.1 Contract NAS8-20547 Through Contract NAS8-26487

The lunar drill frame was being designed to provide maximum rigidity and adequate load bearing capability within the confines of the overall drill weight limitations. Figures 5-29, 5-30, and 5-31 show a mockup of the lunar drill being unfolded and erected.

The frame provides for four-point mounting to the side of the LM. The mounting brackets use quick disconnect pins and when disconnected, the frame folds into a compact package for easy storage and transportation as shown in figure 4-3. The supporting members of the frame are made of 1.5-inch aluminum rods of 6061-T6 alloy and are designed to withstand 400-pound downward thrust on the drill and 4000-pound upward force. Bushings through the upper platform provide lateral support for the hoist pulley support frame.

Figure 5-29. Lunar Drill Mockup - Folded

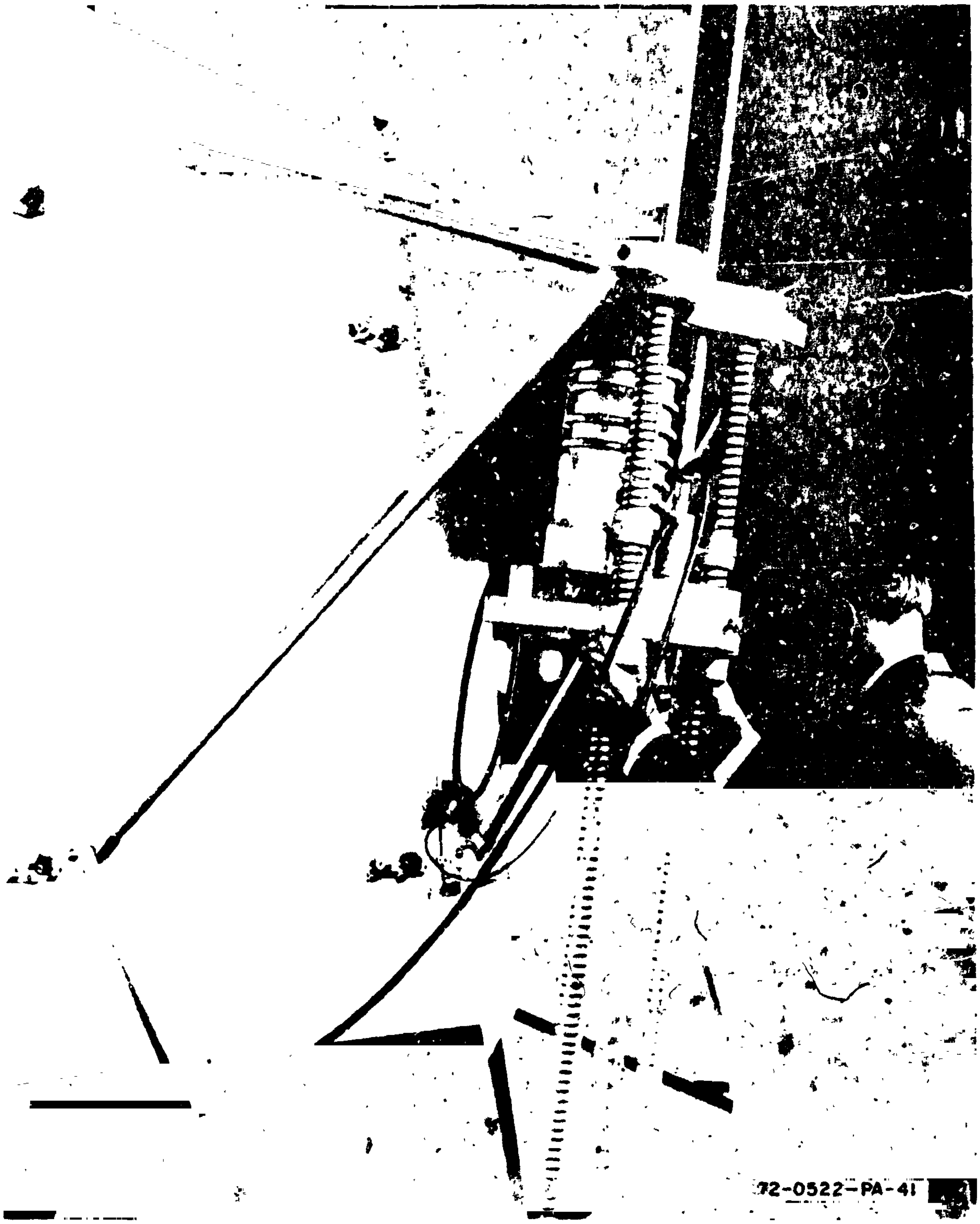

Figure 5-30. Lunar Drill Erection

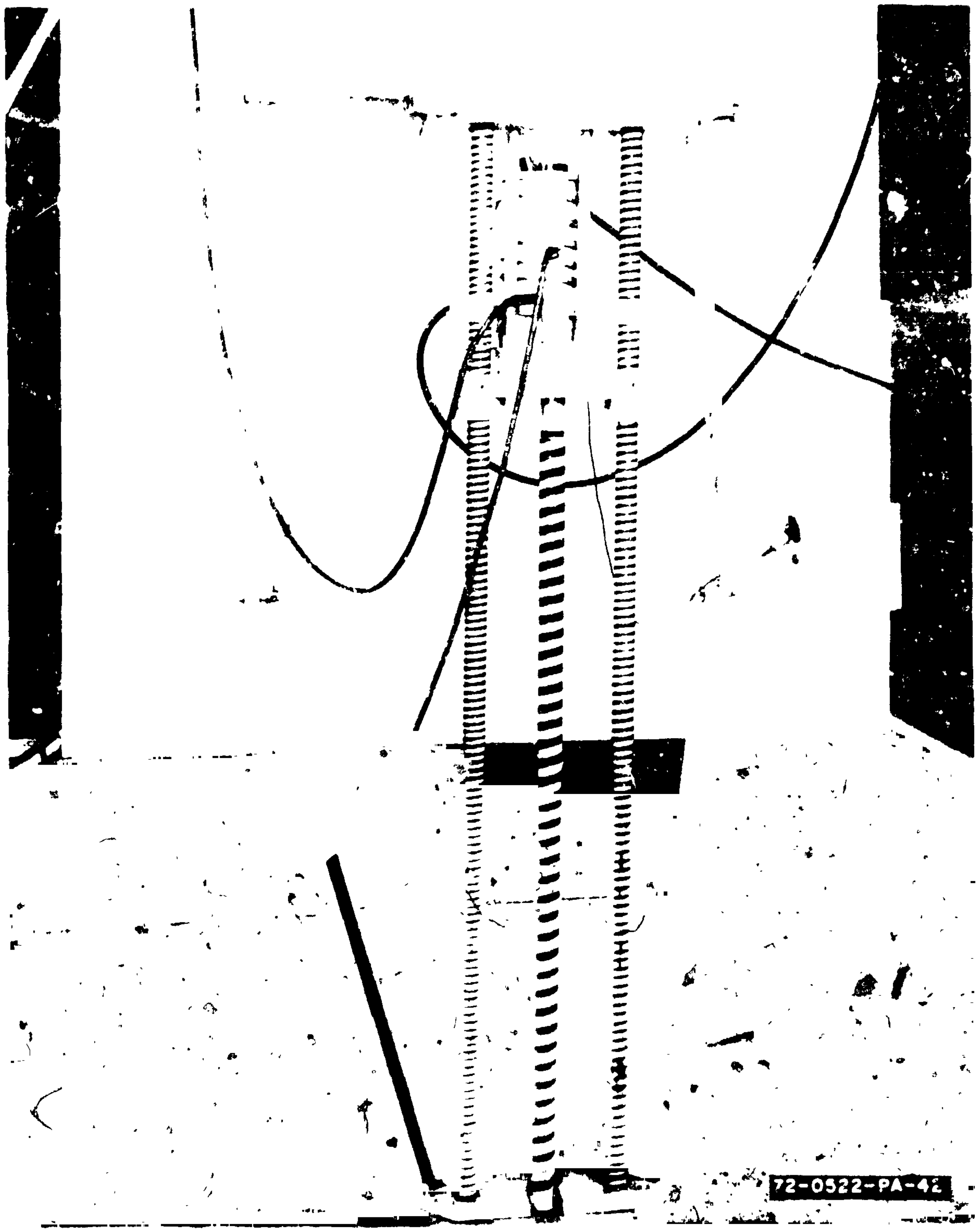

Figure 5-31. Lunar Drill Erected

The hoist pulley support frame is used to provide the height necessary to retract the inner core barrel from the ID of the drill string. The wireline passes over the pulley at the top of the hoist down to the winch. Originally, the winch was operated from the hysteresis clutch which was part of the gearbox mechanism and later by a separate reversible motor. The upper and lower platform, hoist, and winch are made of 356-T6 alloy aluminum.

The ball screws are of special lightweight construction to minimize the overall system weight. The screw threads are ground on hollow steel tubes of SAE 8620 alloy. The ball nuts are part of the gearbox mechanism, and the thrust and core breaking force is applied to the drill string through the ball screws.

The upper and lower platforms serve as attachment points for the supporting frame and as mounts for the ball screws which support the drilling mechanism. Originally, steadying collar was attached to the top of the lower platform to prevent the core barrel from wandering or vibrating excessively when collaring a new hole, and a foot clamp was to prevent the drill string from dropping down the hole when lengths of drill string are being detached during drill string retrieval. During contract NAS8-20845, the functions of the steadying collar and the foot clamp were combined in a design by MSFC. This worked well although a harder type material is needed for the rollers.

Laboratory experience with the drill frame, in general, has been satisfactory. Measurements have indicated that the rigidity of the system is consistent with good drilling practice. No problems of excess distortion or vibration have arisen. To provide additional stability, two additional braces were fastened on the bottom platform. The frame appeared to meet the design load requirements with minimal strain. The method of locking it into position on the simulated side of the LM could be made less demanding upon the astronant's physical capabilities and dexterity.

5.11.2 Future Development Recommendations

Although the frame design has worked out well in the various tests, there are two areas requiring development.

- Study methods of improving the erection and assembly of the drill frame to the LM to ease the astronant's efforts.
- Study methods of providing drill frame stability without the use of two lower stabilizing bars since there are no corresponding hard points for attachment on the LM.

5.12 CASING AND CASING BIT

5.12.1 Contract NAS8-20547

Five feet of casing was provided to prevent cave-in during the first 5 feet of drilling. The casing was furnished in five 1-foot sections which are threaded to form one continuous 5-foot length. A diamond crown was provided on the first section, and auger flights were milled on the outside of the casing. The first section mated mechanically with the drill string diamond coring bit and the casing was driven through this connection. When the casing has been driven to the 5-foot depth, or prior to that into solid rock the drill string is retracted slightly, placed in the rotational mode, and advanced. The mechanical connectors on the casing bit are cut off by the diamond bit and drilling continues normally beyond the casing depth. Figure 5-32 shows the casing bit, and figure 5-33 shows an end view of the coring bit installed inside the casing bit. There was no operational testing of the casing bit design.

5.12.2 Contract NAS8-26487

During this contract a study was made of how to adapt the earlier casing/casing bit design to the downhole hardware produced under contract NAS8-20845. It was concluded that there are several drawbacks to the original design.

a. Chips created by the drill would work their way into the annulus between the casing and the outer core barrel. The wedging of the chips in this space would tend to lock the casing to the barrel and therefore make the drill-through operation with the diamond coring bit difficult or impossible.

C.3.

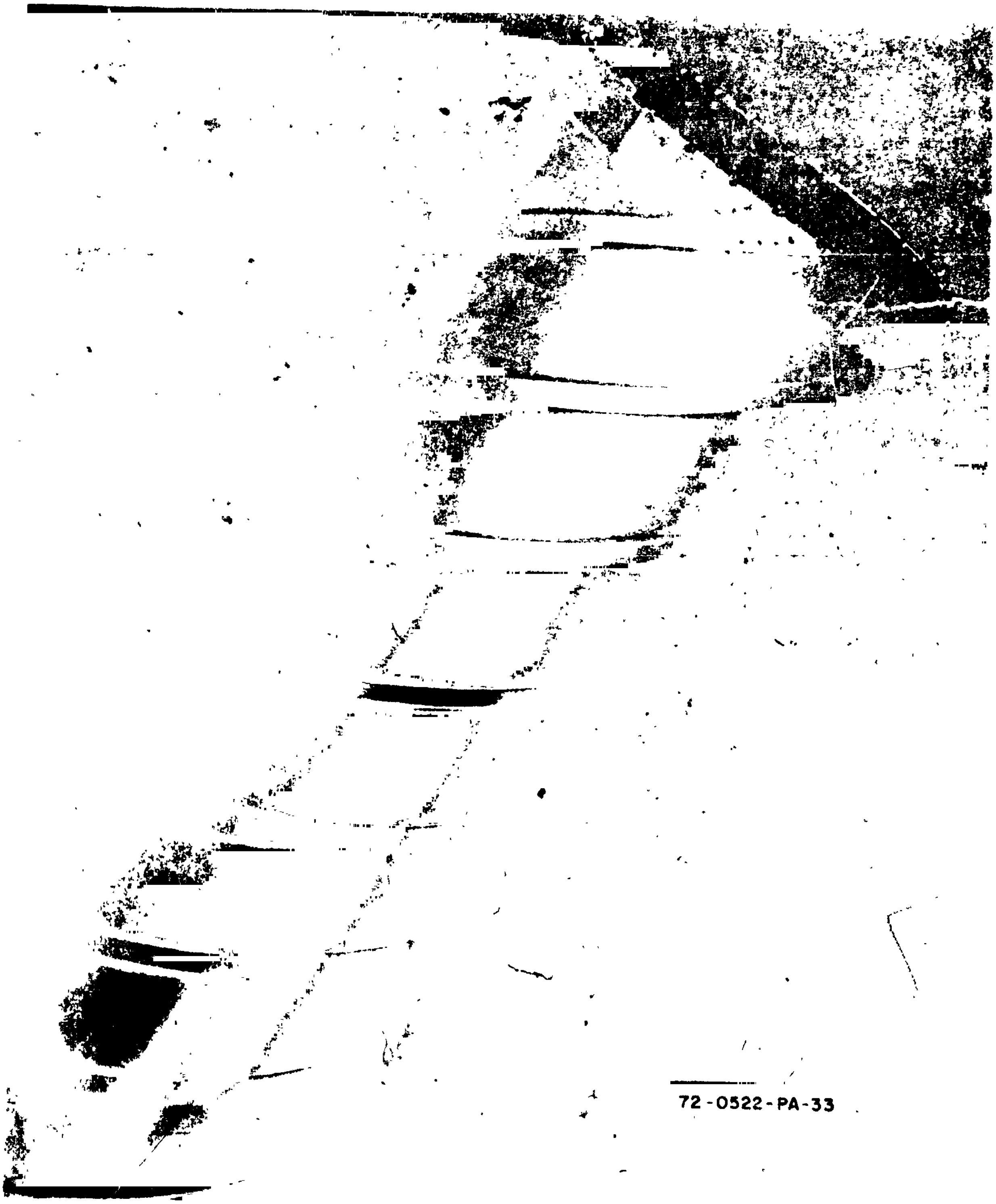

Figure 5-32. Casing Bit

Figure 5-33. Casing Bit in Drill Bit

b. The lack of support for the casing uphole from the bit would lead to wobbling of the casing especially when starting the casing operation. The wobble could damage the diamond bi and auger flights.

c. Since the casing bit only wedges onto the starting bit, there is danger of the two separating when the casing operation begins with the possibility of damaging the diamond bit.

5.12.3 Future Development Recommendations.

It is recommended that this type of design be abandoned and a system designed which would, in essence, utilize a 5-foot core barrel whose ID would permit the regular drill string to pass through. The casing core barrel would fasten to the chuck and be drilled into its full length. The core cut would be broken and withdrawn with a wireline operation. The casing bit would be of a retractable design similar to that developed on contract NAS8-20845. This bit would be retracted to prevent the regular lunar bit from becoming damaged by hitting the ID peripheral diamonds of the casing bit.

5.13 CONTROLS

The drilling operation is controlled normally by a drill operator whose approach is based upon his experience and judgement. The character of the hole and the serviceability of the drill equipment is dependent upon his reaction time and his proximity to the drill controls when a critical situation occurs. It is not unusual for the driller to permit the drill to operate on its own until some action occurs such as the end of the stroke, drill slowdown and excessive vibration, or to achieve faster penetration by taking a "tie the safety valve down" approach to buil the bit through the formation to the detriment of the bit and other downhole hardware.

The astronaut would have neither the time to remain constantly at the controls during his mission nor the dexterity to react quickly to circumstances which might scrub the lunar drill mission. Therefore, a controls concept was developed which would permit the astronaut to preset the thrust and penetration rate parameters which the control carried out automatically when the drill was in operation, would shut the drill down when certain critical values were exceeded, and would indicat the causative condition for the astronaut's corrective action.

5.13.1 Contract NAS 8-20547

Two controls with the associated sensors were developed under this contract. Figure 5-34 is a simplified schematic showing the instrumentation which was furnished for this purpose. Figures 5-35 and 5-36 show both the on-site and the remote control units. The on-site control box contained the logic circuitry necessary to control and protect the drill. The remote control was provided to permit the astronaut to make control setting adjustments or to take corrective action at a nearby point while performing other duties. The remote control is connected to the on-site control by a 100-foot cable. Either control could be used to control the drill system operation.

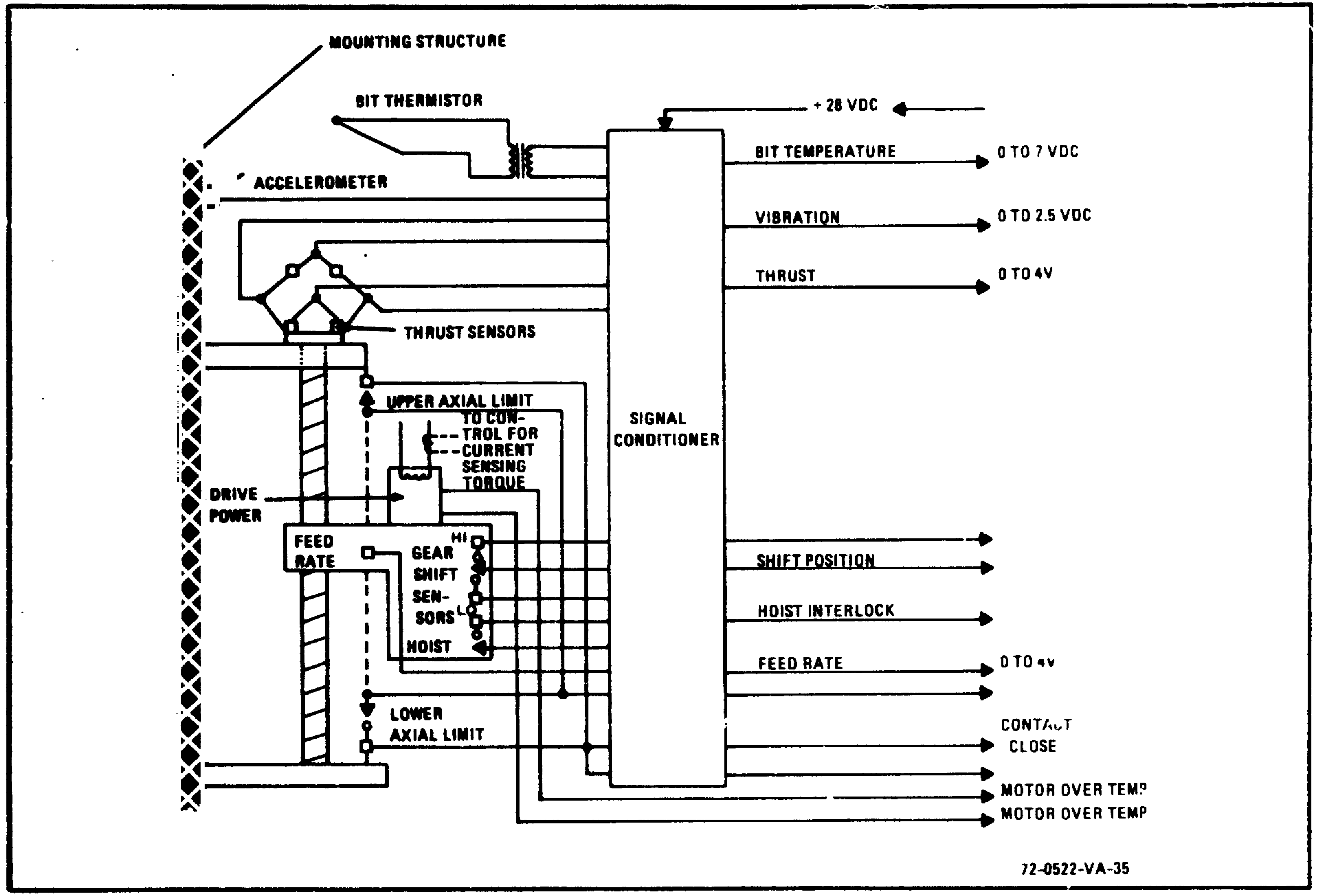

Figure 5-34. Drill Instrumentation

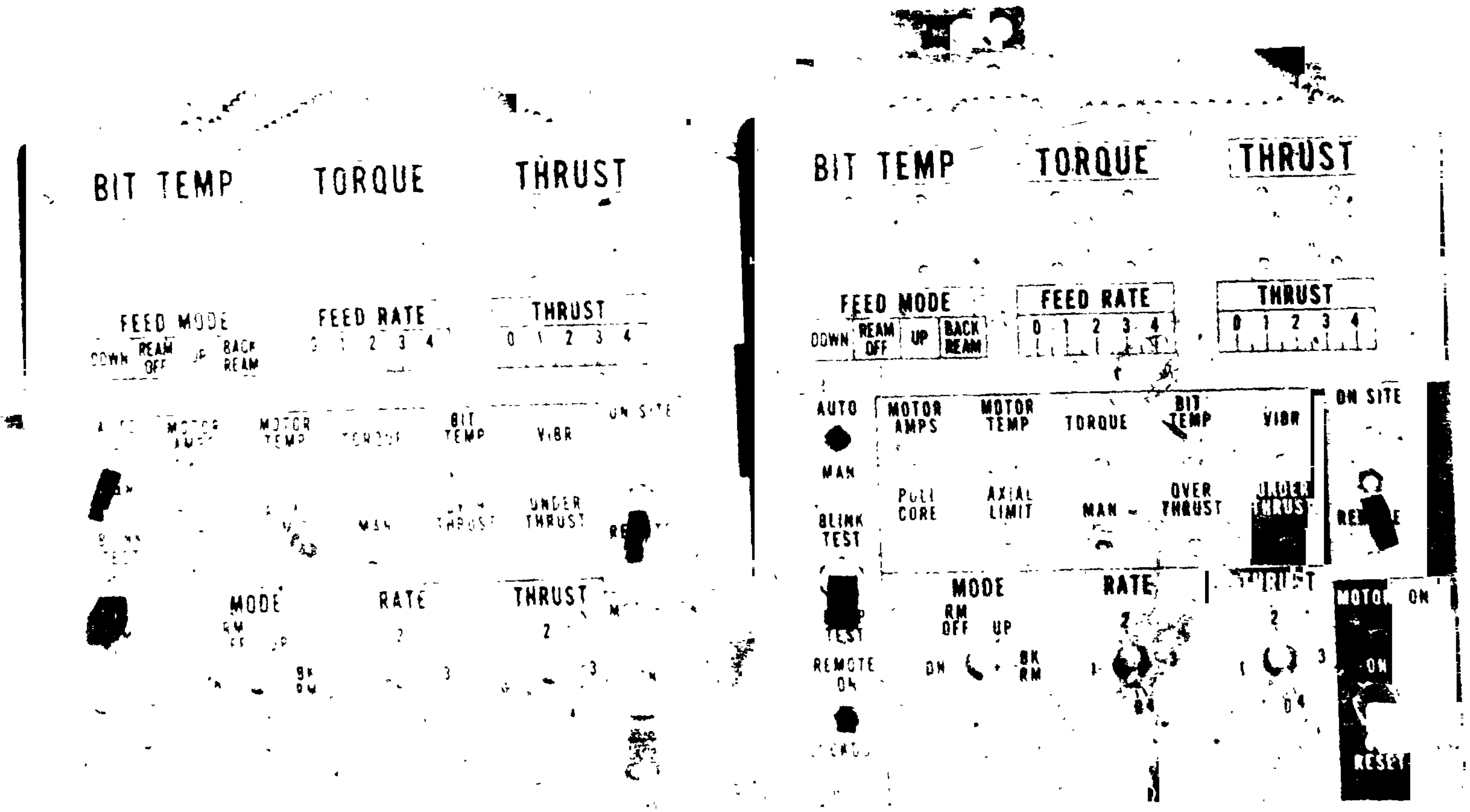

Figure 5-35. Remote and On-Site Controls - Front View

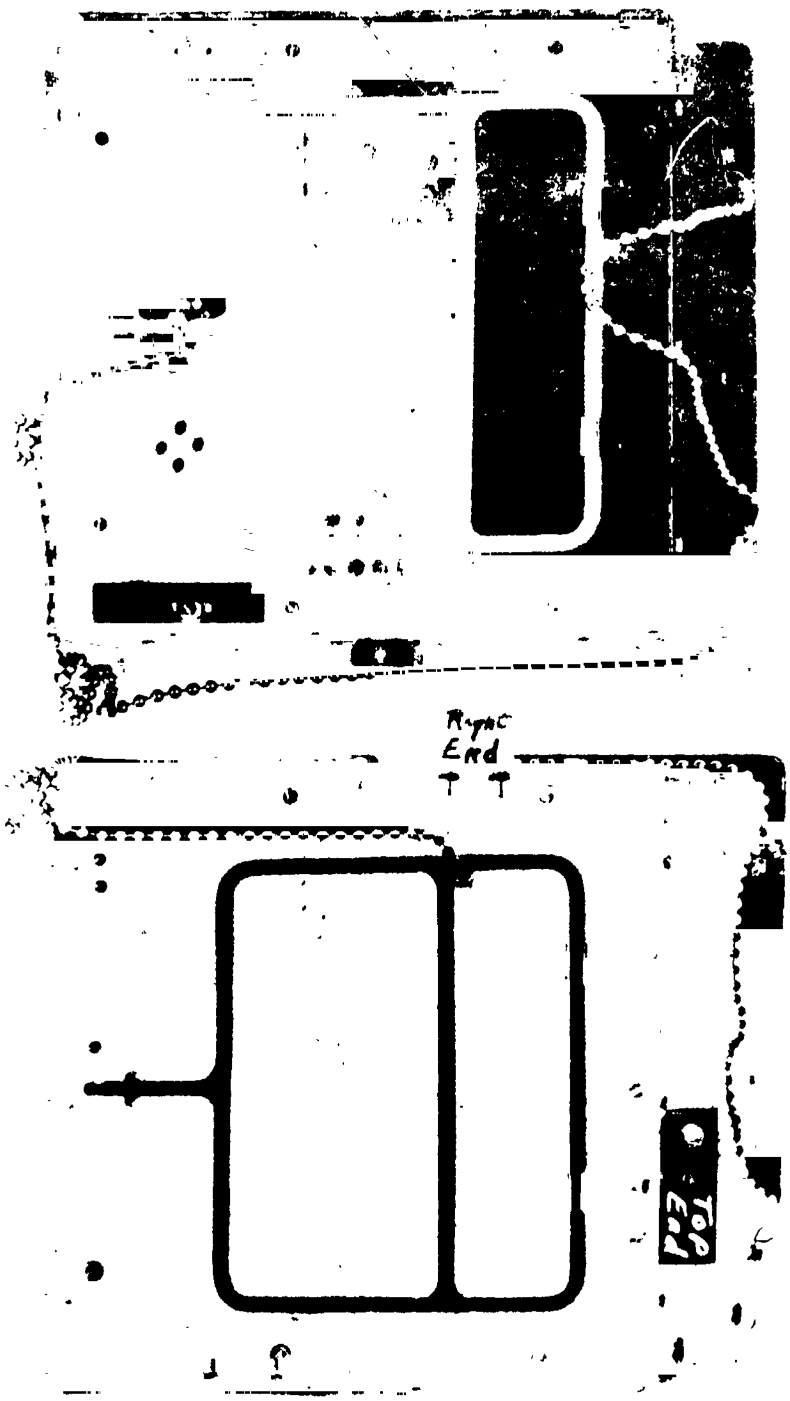

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Figure 5-36. Lunar Drill Controls - Rear View

The functions which could be controlled and/or monitored are shown on the face of the control. Bit temperature, torque, and thrust can be read quantitatively from the meters shown at the top of the panel. The desired values (i.e., values set by the operator for feed mode, feed rate, and thrust) are shown in the second row of instruments down from the top. These settings are controlled by a special keyed control handle (figure 5-34) from the three lower center controls labeled Mode, Rate, and Thrust. The feed mode controls of DOWN and UP indicate the direction in which the drill string is being driven. REAM OFF indicates no travel of the drill string in either the up or down position. Rotation in the ream mode (200 rpm) is possible in this position. The back ream mode allows rotation in the low speed (200 rpm) while the drill string is being retracted. The feed rate is calibrated in inches per minute, and thrust is calibrated in hundreds of pounds.

The 10 lamps shown in the center of the panel are malfunction indications with the exception of the MAN lamp which indicates manual rather than automatic operation. In automatic operation, the activation of any one of these warning lights would cause the automatic shutdown procedure to be activated. This procedure consists of stopping the feed, a 10-second delay to allow the hole to be reamed, then a shutdown of the motor. If the MOTOR AMPS or MOTOR TEMP lights are activated, the 10-second delay is eliminated. A brief discussion of each anticipated malfunction signal is given below.

a. The MOTOR AMPS signal originates in the motor starter and indicates a motor over-current condition.

b. The MOTOR TEMP signal originates from thermally activated switches in the 100-volt motor and indicates excessive temperature in this unit.

c. TORQUE is determined from the motor current and the motor characteristics. This is a gearbox protection rather than a motor protection signal.

d. BIT TEMP is sensed by a thermistor in contact with the bit matrix. This signal is transmitted by wire up the drill string to the rotary joint where a rotary transformer is utilized to pass the signal to the control box. It will cause shutdown at 400°F.

e. VIBR gives an indication of excessive drill vibrations. The sensor is an accelerometer mounted on the surface upon which the drill is mounted. It is primarily a mounting surface rather than a drill protection device.

f. The PULL CORE signal is activated by a combination of thrust of 200 pounds or more and a feed rate of 1/4 inch/minute or less. This indicates that the core barrel is full, a "core block" has occurred, the drill string has fractured, or that a bit has failed. These signals come from the feed rate sensor, which is a dc tachometer geared to a ball screw nut and from the thrust sensors which are strain gauges mounted on the upper arms of the drill frame.

g. The AXIAL LIMIT signal indicates that the gearbox has reached its upper or lower limit of travel on the ball screws. These signals come from magnetic switches mounted on the upper platform of the drill frame.

h. OVER THRUST indicates that the thrust level is in excess of 400 pounds. This signal comes from the thrust sensors referred to in f above.

i. UNDER THRUST indicates a thrust of less than 50 pounds. This signal comes from the thrust sensors referred to in f above.

The upper switch on the right side of the on-site panel permits control of the drill to be switched to either the on-site or remote panel, and the lower switch controls the motor. The top switch on the left allows selection of automatic or manual control of the drill. The center switch on the left is a lamp test switch and the lowest switch locks out the remote control panel. This obviates the possibility of injury to personnel at the drill site by someone inadvertently activating the drill from the remote panel. The remote panel does not have this latter switch.

The gear shift sensors shown in figure 5-33 provide signals to the logic circuitry which provide lockouts so that it is impossible to rotate the drill when the gearbox is in the hoist position and to prevent down feed when in the low speed (200 rpm) gear.

The operational experience which was accumulated with the drill instrumentation and control system was very satisfactory. In general, the controls were sensitive and allow the degree of protection necessary for remote operation. One exception to this general evaluation is the PULL CORE indication. It will be recalled that this light comes on and drilling is stopped when the thrust is over 200 pounds and the feed rate is less than 1/4 inch per minute. Experience has established that during drilling the feed rate apparently fluctuates markedly as the drill bit hits hard spots, as the drill frame flexes, or from other undetermined reasons. Although these fluctuations are normally of short duration (fractions of a second), they are sufficient to indicate to the control system that a core block has occurred and the drilling is automatically stopped. This portion of the circuitry was disabled in order to allow testing to proceed. A recommendation was made that a delay of a few tenths of a second should be built into the system to prevent these short duration variations in the feed rate from stopping the drill.

5.13.2 Contract NAS 8-20845

Diamond dry drilling technology breakthroughs obsoleted or required revisions to be made in the control circuitry under this contract.

Since the bit required no cooling or thermal sensing, the bit temperature, meter and gating circuit, the bit temperature indicator circuit, the bit thermal signal conditioning circuit, and interconnecting wiring were no longer necessary.

Since the maximum thrust had to be raised to 2,000 pounds, some circuit value changes were recommended, however, these were not made.

The small motor, which replaced the hysteresis clutch, was operated by a manual control to apply thrust or to control the vertical movement of the drill head.

Since the lower speed gearing was eliminated during the gearing redesign, the position switches and wiring associated with the "low" setting were no longer necessary.

5.13.3 Contract NAS 8-26487

The control was employed to the degree that it was used to energize the drill and feed motors and ancillary circuitry and for setting the feed mode. The thrust and, hence, the penetration rate was controlled by adjusting the voltage on the feed motor through a manually controlled potentiometer. The penetration rate was recorded on a multipen recorder with the thrust level being recorded simultaneously. A variation in the penetration rate was compensated for by the manual thrust adjustment.

This control method worked quite well but did not prove out that the control could perform as intended during the system test at MSFC.

5.13.4 Future Development Recommendations

The future developments recommended for the control consist of the following:

a. Update the circuitry to be commensurate with the increased thrust limits and remove the unnecessary bit temperature circuitry and indicators.

b. Update the control panel configuration and lettering to reflect the changes made.

c. Change circuitry so that a few tenths of a second delay is introduced to prevent short-term feed rate fluctuations, due to several causes, from shutting down the drill.

d. Update the circuit components to reflect the latest microcircuit design for more reliability and less weight.

6. DRILL PHYSICAL CHARACTERISTIC REQUIREMENTS

6.1 WEIGHT

The delivered weights of the Lunar Drill Engineering Model is shown in table 6-1 for contract NAS8-20547 and contract NAS8-26487.

TABLE 6-1

ENGINEERING MODEL WEIGHTS

	Contract NAS8-20547		Contracts NAS8-20845 NAS8-26487	
Drill Frame Assembly				
1 - drill frame including instrumentation	43 lb		43 lb	
2 - ball screws	30 lb	6 oz	30 lb	6 oz
1 - foot clamp	2 lb	6 oz	3 lb	
2 - drill frame braces	3 lb	2 oz	3 lb	2 oz
1 - lower platform bushing	1 lb	2 oz	-	
	80 lb		79 lb	8 oz
Gear Box Assembly				
1 - gearbox including hoist and feed rate sensor	48 lb	12 oz	48 lb	12 oz
1 - overshot - rotary joint holder		2.5 oz	-	
1 - swivel joint antirotational device		1 oz	-	
1 - chip basket clamp		6 oz	-	
1 - overshot and cable assembly	1 lb	12.5 oz	16 lb	
1 - pressure lubrication system	-		64 lb*	
	51 lb	2 oz	128 lb	12 oz*
Drive Motor Assembly				
1 - AED Sealed Motor - 100 Vdc	34 lb	6 oz	34 lb	6 oz
1 - AED Motor Coolant Pump Assy.	62 lb	14 oz	62 lb	14 oz
or				
1 - AMF Motor - 28 Vdc incl. adapter	27 lb	14 oz	27 lb	14 oz
1 - motor coolant radiator	4 lb	8 oz	4 lb	8 oz
4 - radiator fittings		1 oz		1 oz
3 - flexline hoses	4 lb	14 oz	4 lb	14 oz
AED Motor -	106 lb	11 oz	106 lb	11 oz
AMF Motor -	27 lb	14 oz	27 lb	14 oz

*** Estimated**

TABLE 6-1 Continued

	Contract NAS8-20547	Contract NAS8-20845 NAS8-26487
Controls and Cables		
1 - on-site control and protection unit	7 lb 12.5 oz	7 lb 12.5 oz
1 - remote control	3 lb 8 oz	3 lb 8 oz
1 - interconnecting cable (on-site - remote control)	6 lb 14 oz	6 lb 14 oz
1 - 100 Vdc starter	13 lb 13 oz	13 lb 13 oz
or		
1 - 28 Vdc starter	31 lb	31 lb
1 - signal conditioner	8 lb 11.5 oz	8 lb 11.5 oz
1 - set interconnecting cable	17 lb 2 oz	17 lb 2 oz
1 - 28 Vdc starter - motor cables	20 lb 7 oz	20 lb 7 oz
w/100V starter -	57 lb 13 oz	57 lb 13 oz
w/28V starter -	78 lb 5 oz	78 lb 5 oz
Drill String Assembly		
1 - swivel joint assembly	3 lb 2 oz	-
1 - chuck	2 lb 2.5 oz	2 lb
1 - chuck-core barrel adapter	10.5 oz	-
20 - drill rods	56 lb 4 oz	100 lb*
1 - upper outer core barrel assembly	11 lb 13 oz	11 lb 13 oz
1 - middle outer core barrel assembly	11 lb 13 oz	11 lb 13 oz
1 - lower outer core barrel assembly	12 lb 4.5 oz	11 lb 13 oz
1 - upper chip basket	3 lb 5 oz	5 lb
1 - lower chip basket	2 lb 13 oz	2 lb 13 oz
1 - inner core barrel assembly	5 lb 13 oz	3 lb
1 - bit	8.5 oz	10 oz
1 - bit cooling assembly consisting of:		
1 - bit coolant radiator	19 lb 8 oz	-
1 - valve assembly	4 lb 12 oz	-
1 - flexline water hose	10 oz	-
1 - flexline steam hose	3 lb 1 oz	-
1 - air eliminator	8 oz	-
4 - flexline hose fittings	1 oz	-
4 - casing sections 1 lb 14 oz each	7 lb 8 oz	-
1 - casing bit	11 lb 14 oz	-
	148 lb 7 oz	148 lb* 14 oz

* Estimated

TABLE 6-1 Continued

		Contract NAS8-20547	Contract NAS8-20845 NAS8-26487
Miscellaneous			
1 - fishing tool		13 oz	-
2 - Parmalee wrenches	2 lb 10 oz each	5 lb 4 oz	-
1 - assorted hardware		3 lb *	-
3 - pints of H_2O		3 lb 2 oz	-
1950 ml of U-CON		4 lb 4 oz	-
1 set of tools		-	3 lb*
		16 lb 7 oz	3 lb*
System weight using AED motor -		460 lb 8 oz	525 lb 4 oz**
System weight using AMF motor -		402 lb 3 oz	573 lb**

* Estimated
** Additional weight due to usage of steel in drill rods and the pressure lubrication system for long term system tests.

6.2 VOLUME

The approximate storage volumes are shown in table 6-2.

TABLE 6-2

APPROXIMATE VOLUMES

1 - Folded Drill Frame	2 ft x 2 ft x 8 ft
2 - Stacked Downhole Hardware Components	1 ft x 1 ft x 5.3 ft
3 - Lubrication System	2 ft x 2 ft x 1 ft
4 - Motor Coolant System	3 ft x 2 ft x 1 ft
5 - Starter	2 ft x 1 ft x 1 ft
6 - Controls	1 ft x 1 ft x 1.5 ft
7 - Miscellaneous	2 cubic feet

6.3 MOTOR CHARACTERISTICS

The characteristics of the two motors used are shown in tables 6.3 and 6.4.

TABLE 6-3

SEALED LUNAR DRILL MOTOR CHARACTERISTICS

Part Number	976J551
Outline	See Dwg.
Maximum No Load rpm	9400
Nominal Operational rpm	6000 ±7% at 1.7 lb-ft 4800 ±7% at 5.0 lb-ft
Maximum Input Power at 100 ±2 Vdc	1.7 kW at 1.7 lb-ft 4.0 kW at 5.0 lb-ft
Continuous Rating Torque (100 Vdc, 30 amps)	2.5 lb-ft
Short Time Rating Torque (2 min. out of 20 min.)	5.0 lb-ft
Maximum Start and Stall Torque	93 lb-ft
Maximum Brush Temperature (Normal Operation)	225°F
Maximum Brush Temperature (High Torque)	430°F
Coolant - Maximum Input Temperature	330°F
Coolant - Discharge Temperature	334°F
Total Coolant in Motor	700 ml UCON-50HB55X
Gas Pressure in Motor	10 psig N2 (Dew point 40°F max.)
Rotation (viewed from shaft end)	Clockwise
Weight	34 lb 6 oz

TABLE 6-4

AIR COOLED DRILL MOTOR

Part Number	6615DS02
Outline	See Dwg.
Nominal Ratings	
Input Voltage*	28 Vdc
Input Current	190A
Output	5 HP
Nominal	6000 rpm
Weight	27 lb 14 oz
Rotation (viewed from the shaft end)	Clockwise

* A 28-Vdc, 200-A power inverter has been supplied to provide a suitable motor power input from the NASA ac power source.

6.4 CONTROL POWER SUPPLY REQUIREMENTS

The control power supply requirements are shown in table 6-5.

TABLE 6-5

CONTROL POWER SUPPLY REQUIREMENTS

The dc power system is a 2-wire system. The negative terminal of the power source must be connected to ground.

Control Power Requirements

a. Nominal excursion 25-28 Vdc

b. Absolute maximum excursion 20-30 Vdc

c. 2-3 A maximum required at 28V

d. Maximum ripple voltage - 1.5V peak-to-peak

6.5 EXTERNAL COOLANT PUMP

The characteristics of the external coolant pump is shown in table 6.6.

TABLE 6-6

EXTERNAL COOLANT PUMP

Maximum System Coolant Pressure*	125 psig
Maximum Input Power - Motor	100 Vdc at 3A
Nominal Coolant Flow	2.3 gal/min
Coolant Discharge Pressure**	75 psig
Weight	62 lb 14 oz

* Limited by a relief valve located at the discharge side of the motor coolant pump.

** Limited by a pressure relief valve on the pump discharge bypass.

7. HUMAN FACTORS DESIGN

7.1 CONTRACT NAS8-20457

The drill/astronaut interface was considered strongly in the design of the drill engineering model, and a considerable amount of task analysis was accomplished in the course of the contract. The analyses which were carried out must be considered as extremely tentative in view of the dearth of definitive information available at that time on the drill support structure and transport cargo availability and the fact that many changes were made in the drill design. A comparison of table 12.2, 10th Monthly Report for this contract with table 10.1 of the Operating Instructions Manual indicates that some drilling procedures were changed in line with design and drilling concept changes. For these reasons, the emphasis during the development phase was on the solution of basic engineering problems rather than human factors design effort.

7.2 CONTRACT NAS8-20848

No human factors studies were made during this contract.

7.3 CONTRACT NAS8-20487

It became very obvious during the systems tests at MSFC that the present design of the lunar drill relies too strongly upon astronaut participation. Figure 5-26 shows one example of the type of effort required for uncoupling the drill string.

7.4 FUTURE DEVELOPMENT RECOMMENDATIONS

Experience with the engineering model during Contract NAS8-26487, has indicated that basic engineering improvements must be made in the systems. Since the tradeoff values of astronaut time vs weight may change as better lunar transport capacity is available, it is recommended that any engineering improvements be made with the goal of complete automation in mind, but that emphasis be placed on solving the engineering problems still remaining, and making final tradeoffs in phases C&D.

Such an approach will provide a basis for the design of a more automatic, if not fully automatic system, which should require astronaut attention only in case of malfunction or other unusual conditions. If the problems of weight allocation can be relieved, such a system can be produced.

8. SYSTEM TEST - MSFC

8.1 OBJECTIVE

The objective of the system tests in the MSFC laboratory was to determine if the Lunar Drill Engineering Model was in a condition to withstand the field operation conditions.

8.2 PREPARATION

A number of studies and support efforts were provided under Contract NAS8-26487:

8.2.1 New Feed Motor Study

This study was conducted since there was concern over the field test reliability of the major torque transfer gear in the hysteresis clutch assembly which had been made of solid lubricant for vacuum operation. There was also a desire for faster withdrawal of the drill string from the hole. A small reversible PM dc motor and the mechanical and circuitry changes necessary to adapt it to the gearbox and control circuitry were recommended.

8.2.2 Feed Control Malfunction

During the assembly of the new gearing, lubrication, chuck, and small feed motor into the gearbox by MSFC personnel, it appeared that the torque output of the feed motor was inadequate for the operation. A review of the motor requirements and specifications indicated that the torque should have been quite adequate. Further investigation indicated that the problem lay in the harmonic drive which was misaligned due to a bent flex spline and to the grease employed. These deficiencies were corrected and the feed assembly worked as intended.

8.2.3 Laboratory Test Instrumentation Plan

This study resulted in recommendations for instrumentation required to measure and to record the following parameters.

- Thr . :
- Torque output of drill motor and feed motor
- rpm
- Feed rate
- Depth of hole
- Vibration
- Feed Motor temperature

8.2.4 Laboratory Test Plans and Approaches

The study resulted in recommendations for proving core retrieval and chip removal systems in a variety of drilling environments.

8.2.5 Drill String Disassembly Tool Design

A preliminary design was made for a set of drill string disassembly tools which are self-locking and which cause little damage to the parts of the drill string assembly. These tools, which resemble extra large "vice-grip" pliers, were adaptable to the outer barrel as well as the inner barrel components.

8.2.6 Casing Bit Study

A study of the casing bit approach taken under Contract NAS8-20547 resulted in recommendations that the original casing approach be abandoned and that a new approach utilizing a separately drilled-in casing with a retractible bit be employed.

8.2.7 Inner Barrel Study

This study covered the potential problems with stabilizing the inner core barrel assembly developed under Contract NAS8-20845. One of the results was a recommendation that a new core lifter and case assembly be designed.

8.2.8 Shaft Whirl Study

The core lifter case and its adapter became loose during some early systems tests at MSFC due to a shaft whirl phenomenon. A solution was proposed to seal this assembly into place with a plastic sealant and to remove the core from the upper end.

8.2.9 Core Tensile Determination

During two of the bit break-in tests, the drill string appeared to stick into the hole when the core was to be broken. Although the drill string turned easily by hand when no tension was exerted, the 1-1/2-ton block of basalt could be lifted when tension was exerted. One of the pieces of core was sent to the Bu Mines Twin Cities Mining Research Center for a tensile test. The tensile strength values approached 3,000 psi although the nominal tensile strength expected was 2150 psi. With the core diameter of 1.375 inches, a tensile force approaching 4,300 psi would be required to break the core. The core lifter and drill suffered no damage from lifting the basalt block.

8.2.10 Bit Break-in Test Support

The Westinghouse Program Manager and Technical Director were present as consultants during the initial breaking-in of the diamond bits purchased on a separate contract.

8.2.11 Overshot Design

An off-the-shelf overshot assembly suitable for laboratory and field testing was recommended along with a minor design additions to adapt it to the core barrel assembly ID.

8.2.12 Preliminary Test and Bit Evaluation

After the preliminary tests were run on a basalt block and on a sample of the foamed rock, it was concluded that the Lunar Drill Engineering Model was in a good technical condition to proceed to the deeper hole test in the simulated lunar subsurface.

Bit 20-52, purchased on a separate contract, was damaged during a break-in test. A joint evaluation with the bit supplier indicated that the bit design and manufacture appeared adequate. The damage appeared to be the result of an unusual chatter which occurred during break-in.

8.2.13 Core Lifter Study

The core barrel study resulted in a recommendation that a new core lifter be designed to replace the one developed under Contract NAS8-20845. Working through the bit supplier, Hoffman Diamond Products, Inc., a new core lifter, core lifter case, and adapter design were achieved. Two sets were delivered and worked well after an additional heat treatment of the core lifter.

8.2.14 Laboratory Test Support

During the systems test in the simulated lunar subsurface, the Program Manager and Technical Director acted as consultant to advise and to evaluate the drill system function and difficulties.

8.2.15 Simulated Lunar Subsurface

To test the lunar drill system, a moderately deep simulated lunar subsurface had to be designed and built. Several types of rocks (basalt, vesicular basalt, schist and dacite) were selected by NASA, MSFC to form the subsurface since these rock types are similar in drilling characteristics to the lunar rocks brought back by the Apollo missions. Ten steel hollow cylinders (2-1/2 ft diameter x 4 ft long) were carefully filled with the various types of rocks to represent several strata combinations, and these were oriented to represent a full range of drilling situations. Each rock was mapped in asimuth, elevation, and dip, and each layer of rocks was photographed. From this data, the type of rock being drilled and the drilling situation could be determined at any time during the drilling operation.

A means of holding the rocks in place was required to maintain their positions during the stacking of the rock-filled cylinders to form a 40-foot tower and during the drilling operation. Since a loaded cylinder could weigh a ton, the rock binding material had to be strong enough to support the rock mass and to cement it to the cylinder. At the same time, it had to be low enough in density so that it would produce no adverse effect on the drilling operation. The material could not be flammable and could not produce gummy deposits under the bit drilling temperatures. Since the drilling is a "dry drilling" operation, the material could not contain much moisture, since excess moisture could cause chip agglomeration problems. Above all, the material had to be relatively inexpensive since the unoccupied volume in the tower could require a large amount of binding material.

A study was made to consider means of stabilizing the various rock types and shapes in a simulated lunar subsurface built for the MSFC Laboratory tests. A plastic foam appeared to provide the best chance of meeting all of the requirements as well as being able to fill the irregular interstices between the rocks. The number of fire retardant plastic foams which could meet the other requirements were found to be few in number. The best canidate appeared to be a foam system consisting of a Hetrofoam 368* and Polyphenylisocyanate 293. This foam exhibits excellent fire retardant capabilities and maintains good physical properties on extended exposure to elevated temperatures and high humidity conditions. The range of foam densities could be established between 4-20 lb/ft^3, and the compressive strength could range from 35-100 psi at 75°F depending upon the density. After it hardens, it contains less than 0.2 percent water, and under normal circumstances, it does not absorb moisture under 100 percent relative humidity conditions.

* Durez Division, Hooker Chemical Company

Since the diamond drill bit normally operates at 300° to 400°F in hard rock, tests of the foam were made to determine what problems might be caused by these temperatures. The material expanded slightly when exposed to 300°F-400°F for long periods, and it disintegrated into a black powder when exposed on a short-term basis to temperatures over 700°F. Neither of these results appeared to have a potential detrimental effect on the drilling operation.

Other experimentation indicated that the heat sink characteristics of the rock resulted in limiting the foaming reaction. Heating the rock above 120°F and adding a surplus of blowing agent eliminated the largest part of this problem. The blowing agent evaporated quickly at the rock temperatures and made it difficult to obtain a consistent low density foam. The best estimate of the average foam density was 11-12 lb/ft^3.

The formulation, which appeared adequate for the task, was as follows:

Part A	Hetrofoam 368	119 grams
	Triethylamine (catalyst)	0.1 grams
Part B	Polyphenylisocyanate 293	100 grams
	Genatron 11 (blowing agent)	15 grams
	DC 193 (surfactant)	1 gram

Part A was preheated to 130°-140°F prior to adding the catalyst. All ingredients of Part B were mixed at room temperature. Part B was added to Part A and mixed slowly at first and then at a relatively high speed from 1-1/2 to 3-1/2 minutes depending upon the batch size. The combination was mixed thoroughly with the sides of the container being scraped to assure that the unmixed material was freed up.

The cylinder had been loaded with rocks in an enclosure which was heated above 120°F with a space heater prior to foaming. Since the volume of the cylinder not occupied by rocks was unknown, the liquid mix was poured in 1 gallon increments so that overfilling would not occur. This small mass of foaming material also acted as a control of the exothermic reaction heat, which can be excessive during reaction of large masses of [illegible].

The cylinders had been placed upon plastic sheets prior to being filled with rocks so that during the foaming operation, the foam would not cement the cylinder to the floor. A plywood cap was placed upon the top of each cylinder after the last pour to assure a flattop surface. To avoid accidental overfilling, holes were bored in the plywood to permit the excess foam to exit.

After all the cylinders were foamed, they were stacked and braced to form a 40-foot column (figure 8-1). The lunar drill model was mounted above the tower (figure 8-2) on a mounting frame which was designed to be shifted so that holes could be drilled at selected points. Support was given in preparing the formulation and setting up the application procedures for the foaming techniques at MSFC.

8.3 SYSTEM TESTS

8.3.1 Drill Rate Program

The drill rate program used on the simulated lunar subsurface was as follows:

a. Start at 2.7 inches/minute at less than 1200 pounds thrust.

b. Continue at that thrust until the feed rate fell to 2.5 inches/thrust.

c. Continue 2.5 inches/minute until the thrust reached 1500 pounds.

d. Continue at 1500 pounds thrust until the feed rate falls to 1 inch/minute.

8.3.2 Test Operation

The tests were conducted by MSFC personnel, and data were recorded for thrust, penetration rate, and rotational speed. The penetration rate was kept constant at the values planned except when it was evident that the bit had entered a cavity between the rocks. The operator then reduced the feed rate motor speed so that the bit would not experience a damaging rock

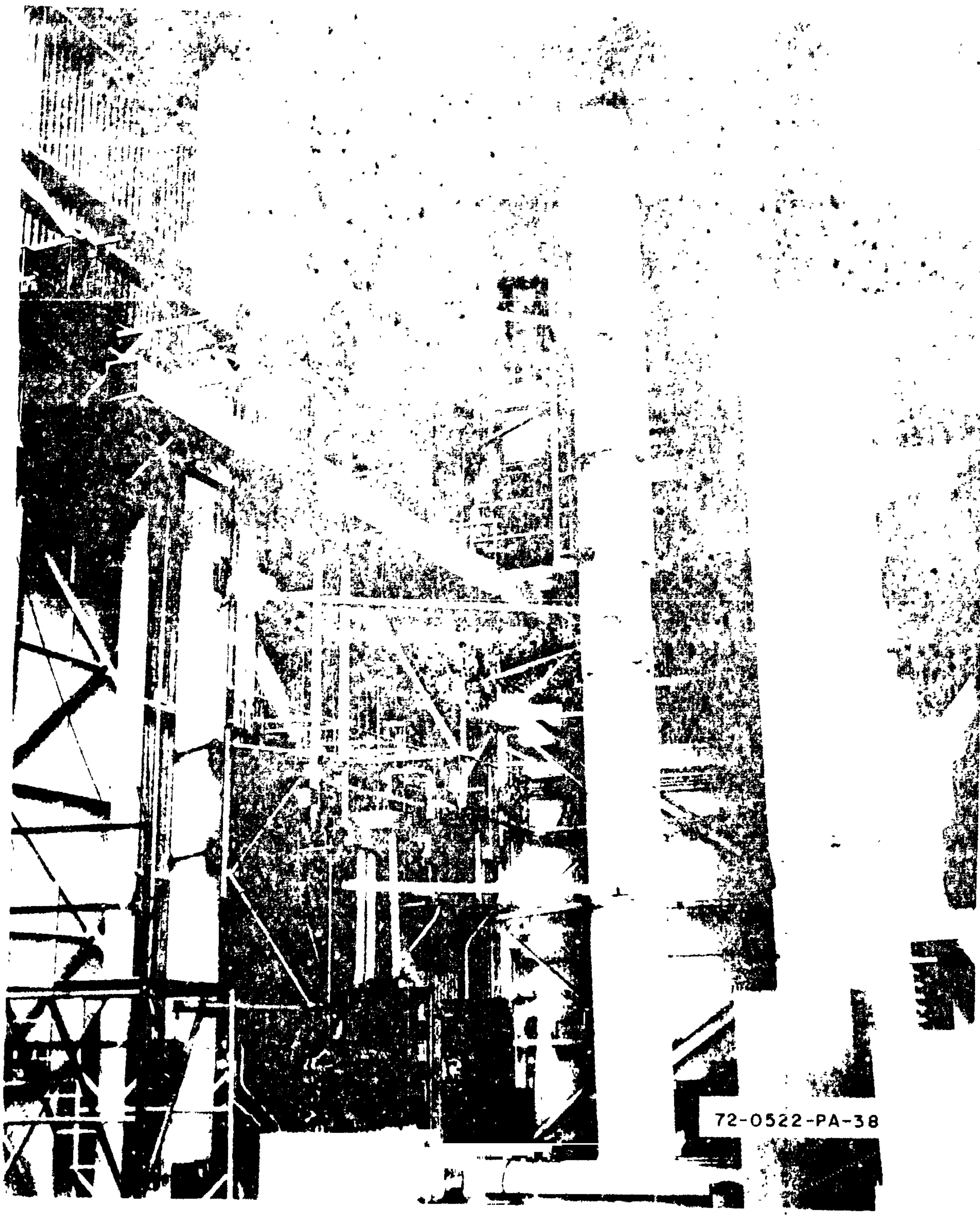

Figure 8-1. Simulated Lunar Subsurface Tower

Figure 8-2. Lunar Drill Drilling in Top of Lunar Subsurface Tower

reentry. The type of rock being drilled by the bit at any time was identified by means of a material/depth chart made up of photographs of major rock layers and their distance from the surface of the tower.

The bit drilled through the rock materials easily, but some difficulty was experienced with dacite core entry into the core lifter due to the chip accumulations on its surface.

All of the lunar drill system component parts performed as designed except for the bit. There were four bits used to drill a total of 95.6 feet.

Hole No	Bit No.	Depth Drilled	Reason for Termination
1	20-48	27'6"	(1) Extreme chatter and high thrust low feed rate.
2	20-50	38'8"	No problems, this is max. depth of hole.
3	20-50	8'	(2) Extreme chatter of drill string.
4	20-50	3.5'	(3) Changed to bit 20-51 new bit.
4	20-51	13'	Lost bit-quartz string in basalt.
4	20-47	51	No problems.

(1) & (2) The extreme chatter was later attributed to a crooked hole.

(3) There was no reason to change bits other than the minor damage of a few fractured stones. This bit was examined by Hoffman Diamond Products, Inc., and was declared a good bit. The tests were terminated to prevent further wear on the drill system. Bits 20-53 to 20-61 were not used in the tests although they were broken in.

8.4 TEST EVALUATION

The performance of the lunar drill system appeared to be satisfactory enough to warrant using it in a field test.

The three areas which may be of a source of difficulty and on which further effort must be made before the field test are:

a. Provide more clearnace on the core lifter to avoid chip jams.

b. Add more height to the hoist pulley support frame and make it stronger so that it can operate with the new overshot.

c. Run the bits in a test to determine if higher thrusts will not improve the life of the bit since much of the hole drilling was performed at 400-800 pounds thrust. This low a thrust may produce diamond wear and contribute to the excessive chatter that occurred before bit wearout.

9. RECOMMENDATIONS FOR FUTURE DEVELOPMENTS

9.1 CURRENT LUNAR DRILL DESIGN

Section 5 contains recommendations for future development for each of the Lunar Drill components which were developed under the objectives and constraints of Contracts NAS8-20547 through NAS8-26487.

9.2 FLIGHT MODEL DEVELOPMENT

During the development of the rotary diamond bit, under NAS8-20845, it was determined that a maximum thrust reactance of 400 pounds pounds insufficient to produce a desirable drilling rate or to achieve the 100-foot bit life. The optimum thrust reactance range for the lunar bit was determined to be from 800-2000 pounds depending upon the bit condition and rock type. The original limits of 400 pounds thrust reactance was set somewhat arbitrarily based upon an estimate of what it would take to tip over the Lunar Module, if it assumed a near critical angle upon landing.

The drill weight objective of 200 pounds mass required that the drill structures be extremely lightweight. Therefore, the drill frame exhibits a degree of flexibility under the thrust vibration and core breaking stresses. During an actual lunar mission, these stresses would be transmitted to the Lunar Module on which the drill frame would be mounted. It is quite conceivable that these transmitted stresses could prove damaging to the Lunar Module and its equipment and could prove to be detrimental to the ascent stage liftoff.

In addition, the single experience with drilling basalt in a moderately hard vacuum indicated that the gases retained in the basalt during solidification were released during drilling. The released gases blew the chips out of the hole at high velocity covering the vacuum chamber (approximately 5 ft. above the drilling surface) with a heavy chip coating. If the lunar rock were formed similarly, it could be anticipated that the chip eruption could occur presenting a safety hazard to the astronauts and to the mission equipment. Drilling into a gas pocket (if such exists) could produce a blowout with its attendant hazards. Under the present weight restraints, no blowout protection could be included.

In summary, it would appear advisable for safety reasons that the lunar drill be removed from the LM to reduce the damage potential and to make provisions to keep the astronauts from being in close proximity to the drill during drilling operations.

The limited manual dexterity, the physical capability of the astronauts, and the large number of other tasks to be performed per mission appears to indicate that the drill system should be made more automatic.

This approach would not eliminate the lunar drill developments already made but would build upon these developments.

Initially, a man/machine/mission interface study must be performed to optimize this relationship.

These studies would probably require that:

a. A new drill support structure be developed including provisions for easy assembly by the astronauts

b. An easy and quick method of tying down the support structure be developed.

c. A power supply be developed to power the drill at its drilling site.

d. A more universal combination of items 1, 2, and 3 be developed if new mission requirements indicate that the drill should be designed to be fastened to a vehicle for transportation to a distant site or a number of sites. A means of fastening the vehicle to the lunar surface during the drilling operation should be provided also if the mission requirements forbid the drill off-loading.

e. Automation of the drill string assembly, disassembly, and storage of the downhole components be developed to reduce the physical efforts and the necessity for constant attendance of the astronauts during the drilling operation.

f. Control circuitry be developed to be compatible with the automation requirements.

APPENDIX A
LUNAR DRILL TECHNOLOGY UTILIZATION

The Moderate Depth Lunar Drill Program produced a series of technology breakthroughs and developments which will have important impacts upon drill equipment design and drilling operations here on earth.

Drilling hard rock was accomplished with the bits exhibiting longer lives than the conventional drills using the liquid or compressed air chip flush. This technological breakthrough was accomplished by applying new diamond selection, setting, and bit manufacturing techniques, by developing new chip handling and storage methods, and by defining and automatically controlling the optimum operational parameters. The benefits to the user will be in longer bit life and fewer drill string removals, lower power requirements, less operator skill and no requirement for ancillary equipment such as water tankage, pumps, compressors, etc., all adding up to a lower cost/ foot of hole for dry rock drilling.

In addition, in coring operations during mineral exploration and soil mechanics sampling, the absence of a liquid chip flush assures an undisturbed sample.

The bit design can be used with liquid or air chip flush as well as drilling dry. Tests have indicated that even longer bit lives can be expected using water chip flushing, and it is expected that air chip flushing will also result in a longer bit life.

A new type of auger developed by Westinghouse gives promise of the downhole hardware being a direct replacement for existing drill strings. It may be the vehicle whereby all of the Moderate Depth Lunar Drill technology can be employed in drilling semiwet and wet formations.

Bit cost/foot of hole is heavily dependent upon the number of times the diamonds can be reset. In ordinary commercial practice, the bits are run under increasing thrust until there is little diamond left above the matrix. Also, the matrix material is selected so that it will wear away exposing more of the diamond for use resulting in a smaller amount of diamond recovery. The lunar bit studies showed that there was an optimum thrust/load bearing diamond beyond which the major mode of diamond failure is fracture rather than wear. The studies also showed that the bits became very inefficient after approximately 0.006 in of wear. If drilling is continued beyond this point at the optimum thrust, the diamonds wear extremely rapidly to failure. Despite this apparent small amount of wear, the lunar bits had longer lives than the commercial bits in hard rock.

Since less than 10 percent of the stone is worn away in the lunar bit before salvage, the stones can be reset more times and more easily than the more heavily worn and fractured commercial bit stones. Although the cost of the lunar bit stones is higher, the diamond cost/bit is lower due to the higher diamond salvage value and to there being fewer stones/bit.

A retractible bit system was developed which permits the worn bit to be replaced without removing the other drill string elements. The greatest impact of the retractible bit will be in deep oil well and mineral exploration drilling operations where drill string removal cost is very high.

Table A1 compares the Lunar Drill technology with commercial drilling practices. Table A2 lists potential applications of Lunar Drill Technology.

TABLE A1

COMPARISON LUBAR DRILL ADVANCES VS COMMERCIAL DRILLING PRACTICES

	Dry Drilling	Commercial Drilling
Automatic Control	Controls drill operations automatically within preset levels and reacts to prevent drill damage due to unanticipated problems.	Driller controls manually and operates by seat of pants approach. Manual control too slow to react to drill damaging situations.
Rotary Diamond Bits	Fewer diamonds, longer life, faster cutting. Retractable bit looks feasible - cutting down number of drill string removals.	Many designs depending upon user preference. No feasible retractable bit.
Dry Subsurface Drilling	Requires no water or compressed air supply to remove chips.	Requires water or compressed air supply to remove chips with the attendant pumps storage containers, piping, special gear.
Damp Subsurface Drilling	Present capability limited. New auger development may work equally well.	Good with adequate water supply. Compressed air no good.
Chip Collection System	Integral part of system can be utilized for geological analysis purposes.	Chips flushed out by water or compressed air collected at surface and used as drilling guide.
Mobility	Good - total system lighter weight - appears to be ideal for remote geological exploration.	Less mobility due to requirement for chip removal fluid handling and for larger power drive.

TABLE A1 (Continued)

	Dry Drilling	Commercial Drilling
Power	Less	More
Drill String Handling	Manual	Manual
Hole	More uniform may be cleaner using new auger.	Hole at times damaged by fluids or may have to be cased or sealed to prevent fluid loss.
Manpower	Fewer and lower skills required	More and higher skills. Drillers require 5 to 10 years experience to become proficient.
Cost/Ft. of Hole	Less	More

TABLE A2

POTENTIAL APPLICATIONS OF LUNAR DRILL TECHNOLOGY

1 - **Drilling in arid lands**

2 - **Soil sampling**

3 - **Drilling concrete & masonry**

4 - **Drilling permafrost, ice, and frozen rock**

5 - Underwater drilling

6 - Mineral exploration

7 - Mine rescue and mine venting

8 - Ground water wells

9 . Retractible bits age in oil well and mineral exploration

APPENDIX B

DRAWING LISTS

The drawings and sketches listed in the following tables are in the possession of the MSFC Lunar Drill Program Office in the form of aperture cards and prints.

Lunar Drill
Systems Operations Division
Drawing List

B.1 CONTRACT NAS8-20547 DRAWING LIST

<u>Inner Core Locking Clamp</u>

6600DS01	Clamp Assy
6600DS02	Clamp - Inner Core
6600DS03	Link No. 1
6600DS04	Link No. 2
6600DS05	Locking Pin
6600DS06	Handle
6600DS07	Retainer
6600DS08	Pin

<u>Foot Clamp</u>

6610WH01	Link No. 1
6610WH02	Link No. 2
6610WH03	Link No. 3
6610WH04	Link No. 4
6610WH05	Handle
6610WH06	Bushing
6610WH07	Pad

6610WH08	Pad Retainer
6610WH09	Clamp Arm.
6610WH10	Platform
6610WH12	Spacer
6610WH13	Clamp Assy.

+28V Starter Ass'y

6610WH30	Terminal Plate
6610WH31	Terminal Block
6610WH32	Chassis, Starter
6610WH33	Right Support, Starter
6610WH34	Left Support, Starter
6610WH35	Torque Sensor
6610WH36	Bracket, Relay
6610WH37	Bracket, Resistor
6610WH38	Chassis, Weldment
6610WH39	Bottom Cover
6610WH40	Screen Cover
6610WH41	Straight Strap
6610WH42	Curved Strap
6610WH43	Top Cover
6610WH44	Starter Ass'y
6610WH45	Plate - Torque Sensor
6610WH46	Spacer - Torque Sensor
6610WH47	Time Delay Ckt. Bd.

Electrical Box +28V Motor

6611WH01	Chassis, Electrical Box
6611WH02	End Plate, Electrical Box
6611WH03	Electrical Box - Base
6611WH04	Cover, Electrical Box
6611WH05	Electrical Box - Assy.

Misc. Items

6612DS01	Spring
6612DS02	Instrum. Contact Button
6612DS03	Junction Box
6612DS04	Contacts and Therm. Assy.
6612DS05	Contacts and Therm. Assy. In Bit
6612DS06	Bushing Collar
6612DS07	Bushing
6612DS08	Pad
6612DS09	Assembly - Bushing

MTG Hardware - Cables and Hoses and Wall Mts

6613DS01	Control Panel Mts
6613DS03	Drill Bit Radiator Support
6613DS04	Truss-Motor Radiator
6613DS05	Wall Mt's Radiator
6613DS06	Brace - Motor Radiator
6613DS07	Motor Radiator Side Support
6613DS09	Snap Slide Fastner
6613DS10	Angle Bracket

Drill Main Ass'y

6614DS01	Lunar Drill Ass'y
6614DS02	Lower Platform Brace
6614DS03	Retainer
6614DS04	Hose Retainer Ass'y
6614DS05	LM Panel

Gear Shift Ind and Hoist Brake and Motor Mis.

Mini-Box

6615DS01	Gear Shift Panel
6615DS02	Motor +28V

6615DS03	Plate, Adaptor
6615DS04	Mini Box Modifications
6615DS05	Board-Resistor
6615DS06	Mini Box Ass'y
6615DS07	Hoist Brake Assy
6615DS08	Pad
6615DS09	Angle Support
6615DS10	Frame Support
6615DS11	Frame
6615DS12	Angle
6615DS13	Block
6615DS14	Angle Ass'y
6615DS15	Angle
6615DS16	Handle

Schem. Diag.

6616DS01	+28V Starter Schem
6616DS02	Drill Instrumentation
6616DS03	Thrust Ck't Bd.
6616DS04	100V Starter Cabling
6616DS05	28V Starter Cabling

Basket

6617DS01	Basket Ass'y
6617DS02	Bracket
6617DS03	Shell
6617DS04	Plate
6617DS05	Pad

Signal Conditioner

6618DS01	Signal Conditioner Ass'y
6618DS02	Plate Bottom and Top

6618DS03	Panel Left Side
6618DS04	Panel Right Side
6618DS05	Plate Receptacle
6618DS06	Plate Front
6618DS07	Bracket
6618DS08	Plate Rear

<u>Tachometer</u>

6619WH01	Tachometer - Ass'y
6619WH02	Shim
6619WH03	Plate, Terminal
6619WH04	Chassis, Tachometer
6619WH05	Left Mount
6619WH06	Right Mount
6619WH07	Adapter
6619WH08	Pinion Gear
6619WH09	Adapter Ring
336D050	Starter
336D051	Starter
336D052	Starter

Lunar Drill
Aerospace Electrical Division
Drawing Lists

On Site Control and Protection List

714471	Test Spec	927A402	Terminal
714477	Test Spec	927A495	Semiconductor
714479	Test Spec	927A795	Terminal
714480	Test Spec	928A028	Resistor
714481	Test Spec	928A736	Resistor
714482	Test Spec	928A739	Resistor
714483	Test Spec	928A829	Resistor
108P409	Plate	928A888	Microcircuit
108P484	Plate	929A091	Transistor
15C7991	Screw-Machine	929A178	Transistor
18D3546	Resistor	929A678	Semiconductor
19C7558	Resistor	929A680	Semiconductor
19C7878	Eyelet	929A960	Bracket
19C8355	Rivet	929A961	Bracket
28B8806	Screw	929A962	Tubing
906D715	Capacitor	929A963	Bracket
906D976	Semiconductor	929A964	Guide
908C913	Retainer	929A966	Guide
909C058	Resistor	929A983	Pin
909C790	Resistor	930A005	Meter
909C808	Transistor	930A006	Meter
910C100	Nut	930A007	Meter
910C331	Washer	930A009	Switch
910C785	Terminal	930A010	Switch
911C207	Washer	930A011	Spring
911C208	Nut	930A012	Chain

911C239	Terminal	920A013	Potentiometer
914F298	Transistor	930A020	Taper Pin
914F441	Switch	930A024	Switch
915F237	Control Assy.	930A026	Light
915F427	Bracket	930A028	Cotter Pin
915F438	Outline	930A048	Semiconductor
915F451	Lead Group	930A049	Transistor
917B612	Splice	930A057	Washer
918B105	Nut	930A058	Plate
920B747	Spacer	930A060	Rivet
926A382	Insulation	930A081	Plate
930A082	Washer	941D890	Bracket
930A083	Bracket	941D902	Bracket
930A084	Bracket	941D906	Printed Circuit
930A085	Plate	941D910	Printed Circuit
930A086	Plate	941D926	Printed Circuit
930A087	Channel	941D927	Printed Circuit
930A090	Spacer	941D928	Printed Circuit
930A091	Lead	941D929	Printed Circuit
930A092	Lead	941D931	Printed Circuit
930A093	Lead	941D940	Printed Circuit
930A094	Lead	941D943	Cover
930A095	Lead	941D944	Cover
930A096	Lead	941D949	Switch
930A097	Lead	941D950	Printed Circuit
930A098	Lead	941D951	Printed Circuit
930A099	Core	941D953	Bracket
930A100	Transistor	941D954	Bracket
930A101	Transistor	941D966	Cover
930A102	Microcircuit	941D968	Cover

930A103	Semiconductor
930A105	Relay
930A106	Switch
930A107	u Bar
930A109	Capacitor
930A110	Lead
930A111	Lead
930A112	Header
930A501	Insulation
938D392	Semiconductor
939A924	Core
940D333	Screw
941D873	Printed Circuit
941D879	Bracket
941D881	Control
941D885	Cover
941D888	Cover
941D889	Bracket
941D971	Printed Circuit
941D972	Transformer
941D983	Cover
947B987	Bracket
947B988	Bracket
947B990	Bracket
947B991	Bracket
947B994	Guide
947B999	Handie
948B008	Plate
948B021	Bracket
948B028	Connector
948B038	Pointer
948B041	Bracket
948B042	Bracket
948B050	Plate
948B051	Resistor
948B067	Bracket
948B068	Bracket
948B071	Resistor
948B072	Bracket
948B073	Bracket
948B074	Bracket
948B077	Bracket
948B078	Plate
948B079	Bracket
948B104	Bracket
948B106	Bracket
948B107	Bracket
948B108	Bracket

948B109	Bracket
968B110	NP Stamp
948B111	Microcircuit
948B118	Resistor
955C075	Nut
956C138	Rivet
958C284	Nut
960C203	Channel
962C808	Bracket
962C821	Bracket
962C832	Handle
962C833	Handle
962C836	Coupling
962C840	Bracket
962C841	Coupling
962C914	Bracket
962C915	Bracket
962C941	Transformer
962C955	Transparency
963C392	Extension
976T629	Wiring Diagram

Lunar Drill
Aerospace Electrical Division
Drawing List

Remote Control

714471	Test Spec	930A010	Switch
714472	Test Spec	930A011	Spring
108P409	Plate	930A012	Chair
108P484	Plate	930A013	Potentiometer
19C7878	Eyelet	930A020	Taper Pin
19C8355	Rivet	930A024	Switch
28B8807	Screw	930A026	Light
906D976	Semicord	930A028	Pin
908C913	Retainer	930A048	Semiconductor
909C058	Resistor	930A049	Transistor
910C100	Nut	930A057	Washer
910C331	Washer	930A058	Plate
910C785	Terminal	930A060	Rivet
911C207	Washer	940D333	Screw
911C208	Nut	941D873	Printed Circuit
914P441	Switch	941D876	Bracket
915F236	Remote Control Ass'y	941D877	Bracket
915F401	Bracket	941D881	Control
917B612	Splice	941D882	Cover
918B105	Nut	941D883	Cover
926A382	Insulation	941D884	Cover
927A402	Terminal	941D885	Cover
927A695	Semiconductor	941D888	Cover
928A829	Resistor	941D889	Bracket
929A178	Transistor	941D890	Bracket

929A680	Semiconductor
929A960	Bracket
929A961	Bracket
929A962	Tubing
929A964	Guide
929A966	Guide Bar
929A983	Pin
930A005	Meter
930A006	Meter
930A007	Meter
947B994	Guide Ass'y
947B999	Handle
948B008	Plate
948B011	Bracket
948B016	Bracket
948B021	Bracket
948B024	Bracket
948B028	Connector
948B038	Pointer
948B040	NP Stamp
948B050	Plate
948B051	Resistor
948B118	Resistor
956C138	Rivet
958C284	Nut
960C203	Channel
926C808	Bracket
962C809	Bracket
962C810	Bracket
962C821	Bracket
941D892	Switch
941D893	Bracket
941D907	Wiring Diagram
941D917	Outline
947B987	Bracket
947B988	Bracket
947B989	Bracket
947B990	Bracket
947B991	Bracket
947B992	Bracket

962C832	Handle
962C833	Handle
962C836	Coupling
962C840	Bracket
962C841	Coupling
926C866	Lead Group
962C956	Transparency
963C392	Extension

Lunar Drill
Aerospace Electrical Division
Drawing List

Motor

5D7137	Terminal	929A946	Nipple
8C7717	Bearing	929A947	Dust Cap
347356	Test Spec	930A021	Packing
674180	Test Spec	930A022	Ring Seal
714356	Test Spec	930A023	Seal
11D5744	Carrier	930A056	Connector
14C4767	Rivet	930A078	Lead
15C8278	Pin	939D515	Nut
15D7602	Arm	941D837	Ring
19C7882	Holder	941D838	Frame
19C7883	Spring	941D847	Stator
22D9444	Terminal	941D852	Housing
23B2588	Holder	941D856	Tube
25B9810	Holder	941D857	Housing
28B8800	Screw	941D858	End Bell
28B8801	Screw	941D859	End Bell
28B9346	Set Screw	941D860	End Bell
909C986	Switch	941D872	End Bell
910C121	Screw	941D875	End Bell
910C331	Washer	941D895	Impeller
910C886	Packing	941D947	Stator
910C901	Screw	947D862	Insulation
915F338	Housing	947D864	Insulation
915F339	Housing	947D865	Insulation
915F340	Stator	947D866	Insulation
915F341	End Bell		

915F343	Armature
915F350	Outline
920B566	Ring
924A275	Spring
929A913	Insulation
929A914	Insulation
929A915	Lead
929A920	Lead
929A921	Lead
929A941	Lead
929A942	Lead
947B934	Lead
947B935	Lead
947B936	Lead
947B957	Spacer
947B959	Insert
947B961	Ring
947B965	Lead
947B966	Insert
947B967	Tube
947B968	Bar
947B972	Retainer
947B974	Ring
947B975	Seal
947B976	Spacer
947B977	Spacer
947B978	Tube
955C165	Packing
955C170	Screw
962C682	Punching
947D867	Insulation
947D868	Insulation
947D869	Insulation
947D870	Insulation
947B871	Diagram
947B872	Washer
947B873	Lead
947B876	Lead
947B903	Deflector
947B925	Commutator
947B926	Wedge
962C792	Cover
962C793	Frame
962C800	Ring
962C801	Hub
962C802	Impeller
962C858	Impeller
962C904	Baffle
962C909	Ring
962C910	Baffle
976J551	Motor Ass'y

962C683	Pole
962C684	Pole
962C730	Commutator
962C747	Coil
962C748	Coil
962C749	Coil
962C750	Coil
962C751	Coil
962C755	Holder
962C756	Brush
962C760	Punching
962C761	Punching
972C762	Insulation
962C773	Coil
962C781	Shaft
962C782	Shaft
962C784	Shaft

Lunar Drill
Surface Division
Drawing List

Heat Exchangers

332D306	Motor Heat Exchanger
608J272	Bit Coolant Heat Exchanger
332D515	Chassis Valve Ass'y
332D516	Clamp
332D559	Transformer - Rotary
332D560	Rotary Transformer Ass'y
332D552	Switch Holder

Aerospace Division Drawings

Drill Frame

Dwg. No.	Description		
415R522	Fitting-End	415R602	Plate
415R523	Pin	415R603	Plate
415R525	Lanyard	415R604	Angle
415R527	Tube	415R605	Set Screw
415R539	Spring	511R855	Mount
415R540	Bushing	511R881	Support-Hoist
415R541	Retainer	511R882	Support-Hoist
415R545	Fitting-End	511R883	Fitting-End
415R547	Fitting-End	511R884	Fitting-End
415R549	Fitting-End	511R898	Guide
415R551	Sleeve-Crimp	611R556	Base
415R581	Spring	611R558	Brace
415R582	Pulley	611R561	Lower Truss
415R583	Washer	611R562	Upper Truss
415R584	Tube	611R564	Upper Platform
415R585	Tube	611R627	Brace-Torque
415R586	Fitting-End	611R628	Hoist Platform
415R587	Guide	611R555	Platform - Lower
415R592	Gusset	702R524	Lunar Drill
415R593	Tube		
415R594	Fitting-End		
415R595	Plate		
415R597	Bushing		
415R598	Fitting-End		
415R599	Elbow		
415R600	Elbow		
415R601	Elbow		

Christiansen Diamond Products Company
Drawing List

Bit

8267	Process sheet
8267.1	Assembly with drive keys
8267.3	Bushing
8267.14	Thermocouple tube
8267.6	Auger flight
8267.9	Mold without keys
8267.10	Plot sketch
8267.11	Ass'y specification
8267.13	Outer tube
57893	Mfg. spec.

B.2 CONTRACT NAS8-20845 DRAWING LIST

Hoffman Diamond Products, Inc.
Diamond Coring Bit Drawing List

NAS-54-W	Bit Layout
NAS-54-W1	Diamond Location Chart
NAS-54-W1A	Diamond Location Chart
NAS-54-W2	Split Mold Assembly
NAS-54-W3	Split Mold Pin
NAS-54-W4	Split Mold Bottom
NAS-54-W5	Split Mold Assembly Mold Top
NAS-54-W6	Split Mold Assembly Mold Bottom
NAS-54-W7	Bit Blank
NAS-54-W8	Barrel
NAS-54-W8A	Barrel
NAS-54-W9	Kicker Stone Layout
NAS-54-W10	OD Kicker Stone Chart
NAS-54-W11	ID Kicker Stone Chart
NAS-54-W12	ID Kicker Stone Chart
NAS-54-W13	Primary Chip Release Passages
NAS-54-W13A	Large Chip Release Passages
NAS-54-W14	Small Chip Release Passages & 10 Release Inserts
NAS-54-W15	Mold Showing Location of Chip Release Passages
NAS-54-W16	Finished Bit
NAS-54-W16A	Finished Bit
WB 2129	Oil Lubrication System
WB 2194	Connectors & Hose
WB 2125	Tubing
WB 2124	Fitting Tubing & Clamp
WD 2049	Chuck Assembly
WG 2[illegible]18	Gearbox Rework
WF [illegible]04	Core Barrel Assembly

1 - Sketch 28 Volt Motor Starter Revised 12 July 71

2 - Dwg 166A-100-8 Globe Industries Bulletin GRP Motors 2/65

3 - AQ Overshot Assembly E J Longyear Price List 8/15/69

4 - WD 2111 Inner Tube Revised 12/3/71

APPENDIX C

BIBLIOGRAPHY AND ILLUSTRATIVE MATERIAL

Table C-1 covers all of the known written and illustrative material on the Moderate Depth Lunar Drill Program.

TABLE C-1

BIBLIOGRAPHY

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TABLE C-1 Continued

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Motion Picture, "Lunar Drill Bit Test," Bu Mines Mining Research Center, Minneapolis, Minnesota, November, 1969.

Motion Picture, "Lunar Drill Auger Tests," E. J. Longyear Co., Minneapolis, Minnesota. February, 1969.

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Motion Picture, "Lunar Drill System Test," MSFC, Huntsville, Alabama, March, 1971.

NAS8-26175 Lunar Base Synthesis Study, May, 1971.